EFFICIENCY OF DIFFERENT PHOSPHATE FERTILIZER SOURCES IN TWO HAWAIIAN SOILS WITH CONTRASTING PHOSPHATE FIXING TENDECIES

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ABSTRACT

The efficiency of fused magnesium phosphate, treble superphosphate, and treble superphosphate with calcium silicate was studied in a Gibbsihumox, and the efficiency of fused magnesium phosphate and treble superphosphate was studied in a Chromustert. Sudax was the indicator crop in this pot experiment. Also, the efficency of three granule sizes (normal size, coarse fraction, and fine fraction) of fused magnesium phosphate in a Gibbsihumox was studied in the same experiment. In both studies the plant and first ratoon crops of Sudax were analyzed for P,Si, Mg, Ca, K, and Mn. The two soils were analyzed for extractable P, sorbed P, extractable Si, Mg, Ca, K, Mn, Fe, Cu, Zn, and soil pH. Samples from the Halii soil were also analyzed for extractable Al.

The dry matter yields of the plant and first ratoon crops of Sudax increased significantly with increasing levels of applied P in both soils. Treble superphosphate gave significantly higher average dry matter yields than fused magnesium phosphate in the two soils in the plant crop. However, in the ratoon crops average dry matter yields were nearly identical for the two phosphate sources. The application of calcium silicate with treble superphosphate to the Halii soil increased dry matter yields of both plant and ratoon crops, but the increase was not significant.

The three granule sizes of fused magnesium phosphate applied to the Halii soil produced similar dry matter yields.

Plant P concentrations were similar for fused magnesium phosphate, treble superphosphate and treble superphosphate with calcium silicate in the Halii soil; and for fused magnesium phosphate and treble superphosphate in the Lualualei soil. Plant Mg concentrations in the Halii soil were significantly higher for fused magnesium phosphate than for treble superphosphate with and without calcium silicate. In the Lualualei soil, however, plant Mg levels were similar with the two phsophate fertilizers. Plant Si concentrations were highest with fused magnesium phosphate in the Halii soil.

Extractable soil P was significantly higher for treble superphosphate than fused magnesium phosphate in both soils. The addition of calcium silicate with treble superphosphate to the Halii soil increased soil P significantly. The phosphorus requirement of the soil was decreased by the application of calcium silicate. The amount of soil P extracted from the Halii soil for the three granule sizes of fused magnesium phosphate increased in the order fine fraction $<$ normal size $<$ coarse fraction. Phosphorus sorption studies showed that P sorbed by the Halii soil with the three phosphate sources was in the order treble superphosphate with silicate $<$ treble superphosphate $<$ fused magnesium phosphate. In the Lualualei soil the order was treble superphospate $<$ fused magnesium phosphate. Fused magnesium phosphate increased soil pH from 4.1 to 5.6 in the Halii soil with the application of 800 Kg P/ha, and from 7.5 to 7.7 in the Lualualei soil with the application of 200 Kg P/ha. The same amount of fertilizer material reduced the level of soil Al in the Halii soil from 0.7 to 0.2 me/100 g soil.

Fused magnesium phosphate appears to be a suitable source of P for highly weathered soils with high P fixing capacity and low pH, Ca, Mg and Si.

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INTRODUCTION

Many soils throughout the world are phosphorus deficient. Total P content of most mineral soils ranges from 0.01 to 0.13 percent P. This is equivalent to about 200 to 2600 kg of P per hectare, only a part of which is available to plants. Even in the more fertile soils inorganic P concentration of the soil solution does not go beyond 10 m*M* (Arnon, 1953; Fried and Shapiro, 1961). In 135 representative U.S. soils, the inorganic P concentration of the solution did not exceed 8 m*M*, and the modal concentration was 1.5 m*M* (Barber *et al*, 1963). In contrast, the modal concentrations of K, Ca and Mg were 90,700 and 1000 m*M*, respectively.

Low solubility of inorganic P salts is another factor responsible for low P concentrations in the soil solution. In some clay soils much of the inorganic P is completely unavailable because it may be strongly held by the crystal lattice of the mica surfaces. About 98-99 percent of the inorganic P in clay soils can be bound so strongly that it cannot be extracted by salt solutions, exchanged with added p^{32} or utilized by plants.

A considerable part of the soil P is in the organic form. This fraction is mostly colloidal and largely insoluble, and may not be available to plants (Van Diest, 1968).

As a result of the low level of P in soils, phosphate fertilizers must be applied to guarantee optimum crop yields. The effectiveness of added phosphate fertilizers is decreased in tropical soils as well as in some temperate soils by "fixation." This is a process by which P when added to the soil becomes restricted in its mobility and less available to plants (Fox, 1967).

Volcanic ash soils formed under warm, moist conditions in Hawaii are dominated by amorphous clay fractions containing high levels of allophane and hydrated oxides of iron and aluminum (Suehisa et al, 1963). Such soils are characterized by high P fixation.

The problem of P fixation can be reduced by massive applications of P, addition of soil amendments and the use of materials with controlled solubility.

The world production of phosphoric acid (P_2O_5) was about 25.7 million metric tons in 1974-1975 (Statistical Yearbook, 1975), an increase of about 100 percent over the previous 9 year period. In 1976-1977 the production will reach 30.8 million metric tons (FAO, 1974), an increase of 5.1 million tons over the last two years. The consumption this year will be 27.7 million metric tons, leaving a surplus of about 3.1 million tons.

The rapidly increasing demand for high analysis phosphate fertilizers has precipitated a tremendous expansion of phosphoric acid (P_2O_5) manufacturing facilities using new and improved technology. As a result many new phosphate materials are available in the market. The evaluation of the relative efficiency of these phosphate materials under different conditions and in different soils is critical for efficient crop production.

The objectives of this study were:

(1) The evaluation of two phosphate materials (treble superposphate, TSP, and fused magnesium phosphate, FMP) at different rates as sources of P for a plant crop of Sudax grown in two soils having different phosphorus fixing capacities.

(2) The study of the effectiveness of two phosphate materials at different rates on a ratoon crop of Sudax.

(3) The study of the effect of particle size of fused magnesium phosphate (FMP) on the availability of P to two crops of Sudax grown in a Gibbsihumox.

(4) The study of the fixing capacity of a Vertisol and an Oxisol.

LITERATURE REVIEW

Phosphate Fixation in Tropical Soils

In its general sense the term "fixation" is defined as "the process of rendering permanent" (Hance, 1933). It is a general term for processes by which plant nutrients when added to soils become restricted in their mobility and less available to plants (Fox, 1967). The term phosphorus fixation is defined as the process by which the solubility of added phosphate fertilizers is decreased, thus making it less available (Bear, 1967). Dean (1949) defined phosphorus fixed as "the soil phosphorus which has become attached to the solid phase of soils." When phosphates are "fixed" in a soil, they become held so tenaciously by the soil that plant roots can absorb very small amounts. Even large applications of soluble phosphorus may be "fixed" in the soil to an extent that plants may not be able to absorb them fast enough to meet their needs. However, phosphate fixation is not altogether an irreversible process (Younge and Plucknett, 1966; Fox et al, 1968; Fox and Kamprath, 1970).

The process of phosphate fixation involves adsorption reactions, isomorphic replacement reactions, and double decomposition reactions (Kardos, 1955; Bear, 1964).

Phosphate fixation in tropical soils is far more serious than in soils in the temperate zone (Bradfield, 1963). It is one of the most serious problems in agricultural development of the Tropics.

The magitude and rate of phosphorus fixation are a function of several factors, some of which are:

(1) degree of weathering (Godfrey and Riecken, 1957),
(2) mineralogical composition of the soil (Chu and Sherman, 1952; Olson and Engelstad, 1972),
(3) soil pH (Fried and Shapiro, 1956),
(4) alternate wetting and drying of the soil (Patrick and Mikkelsen, 1971),
(5) oxidation-reduction state of the soil (Patrick and Mahapatra, 1968),
(6) concentration of phosphate ions in soil solutions (Fox, 1967),
(7) time of reaction of phosphates with the soil (Fox, 1967),
(8) activity of micro-organisms (Askinazi, 1958),
(9) amount and distribution of organic matter,
(10) soil texture (specific surface area).

Fixation Reactions: Applied phosphates become fixed in acid soils by reacting with soluble aluminum originating from exchange sites or from lattice dissociation and form highly insoluble aluminum phosphate compounds (Hemwell, 1957). Soluble iron and manganese also fix applied phosphates by rendering them highly insoluble.

Phosphate Fixation by Hawaiian Soils: The high phosphate fixation capacity of some Hawaiian soils is attributed to the presence of large amounts of amorphous aluminum and iron, as well as allophanic and halloysitic clay minerals

(Suehisa *et al*,1963). Soils with the highest phosphate fixing capacity are those dominated by hydrated oxides and hydroxides of iron and aluminum (Chu and Sherman, 1952) which have been identified using x-ray, spectrographic and differential thermal analysis methods (Tamura and Jackson, 1953).

In oxides and amorphous colloids, charges arise at exterior lattice positions and are better described by a constant potential model rather than a pH-dependent charge model (Mekaru and Uehara, 1972). The net surface charge of oxides or hydrous oxides of iron and aluminum depends on the concentration of H^+ and OH^- ions, which are potential-determining ions. Phosphate adsorption in soils containing such colloids is very strong because these colloids can acquire net positive charge under acid conditions. The phosphate adsorption capacity depends not only on the amount of free iron oxide, but also on the reactive nature of the oxide surface (Mekaru, 1969).

Phosphate anions can be adsorbed on oxide surfaces by nonspecific anion adsorption (Hingston *et al*, 1967, 1968) or by specific anion adsorption (Dean and Rubins, 1947; Hingston *et al*, 1967, 1968). Hingston *et al* (1967, 1968) defined the nonspecific anion adsorption as the retention of anions as counter ions in the diffuse layer opposite a net positively charged surface. They defined specific anion adsorption as the exchange reaction by which phosphate anions enter into coordination with water molecules or hydroxyl ions of the oxide metal by replacing another anion.

The mechanism of phosphate fixation by kaolinitic clays has been attributed to the aluminum associated with lattices (Low and Black, 1947). Under acidic conditions the kaolinite particles acquire positive charges which can be neutralized by phosphate anions. The addition of phosphate fertilizers to a soil rich in kaolinitic clays will induce decomposition of the clay and cause subsequent precipitation of aluminum phosphate and release of soluble silica (Low and Black, 1947, 1950). The decomposition of kaolinite upon reacting with phosphates and the formation of alumino-phosphate compounds have been reported by other investigators (Murphy, 1939; Kittrick and Jackson, 1955).

Montmorillonite and mica fix phosphates to a lesser extent than does kaolinite (Low and Black, 1947). The active iron and aluminum are the principal sources of fixation capacity in montmorillonitic clays as in kaolinitic clays (Coleman, 1944; Ellis and Truog, 1954). Hawaiian latosols also contain aggregates of gibbsite and goethite.

The relative fixation capacities of the more common components of the clay fraction of Hawaiian soils are in the following order: amorphous hydrated oxides $>$ goethite-gibbsite $>$ kaolin $\geqq$ montmorillonite (Fox _et al_, 1962; Fox et al, 1968; Roy, 1969). It has also been demonstrated that phosphate fixation by subsoils is greater than fixation by surface soils (Fox, 1969).

The pronounced tendency of some Hawaiian soils to "fix" applied phosphates was first investigated in 1902 by Crawley who attributed the reversion of phosphoric acid to the presence of bases. Hance (1933) stated that fixation of applied soluble phosphate in most Hawaiian soils occurred over a variable period of time, well within the normal root zone and was so complete that little or no loss occurred by leaching or seepage. Many other workers reported that Hawaiian soils, especially volcanic ash soils, fix large amounts of phosphorus (McGeorge, 1922; Ayres, 1934; Davis, 1935; Suehisa et al, 1963; Fox, 1967, 1969). The immobilization of phosphorus by Hawaiian soils is rapid and complete (Chu and Sherman, 1952; Fox et al, 1962; DeDatta et al, 1963, Mahilum, 1965).

The removal of oxides of iron and aluminum from the soil reduces phosphate fixation by more than 70 percent (Chu and Sherman, 1952). The removal of the hydrated iron complex alone reduces phosphate fixation by 50 to 60 percent (Younge and Plucknett, 1966). However, Ca-saturated clays treated to remove active iron and aluminum have been reported to fix large amounts of phosphate as calcium phosphate complexes (Ellis and Truog, 1954).

When ammonium and potassium phosphate solutions react with colloidal or thin layers of gibbsite or with aluminous soils at low pH, a crystalline mineral called taranakite may form (Haseman et al, 1950; Terman and Stanford, 1960; Tamimi et al, 1963; Liu et al, 1966). This complex phosphorous-containing mineral has the empirical formula: $2(K,NH_4)_2O.3Al_2O_3.5P_2O_5.26H_2O$.

Effect of Soil pH on Fixation Reactions: Soil pH is a major factor in determining phosphorus fixing capacity of a soil. Phosphate is usually most available to plants in the soil pH range of 5.5 to 7.0 (Tisdale and Nelson, 1975). Phosphorus uptake by sugarcane from a Gibbsihumox in Hawaii was maximum at pH 5.8 (Teranishi, 1968). Hewitt et al (1954) reported that the responses of corn to phosphate applications on bauxite soils of Jamaica were pH-dependent. When pH was below 7.0, there was a significant response to added phosphate, while above pH 7.0 the response was not significant except in soils where available phosphate was very low (less than 13 ppm–Truog method extractable P).

Liming very acid soils or soils high in hydrous oxides of aluminum will reduce phosphorus fixation and enhance phosphorus availability to crops (Schmehl et al, 1950; Olson and Engelstad, 1972). In the tropics there is no benefit from liming soils above pH 5 or 6 (Fox et al, 1964, Kamprath, 1970). Liming acid soils increases phosphorus solubility only in the pH range where aluminum solubility is high and will decrease rapidly with increasing pH.

Correction of Phosphorus Fixation: The tendency of soils to fix added soluble phosphates can be overcome by several approaches, some of which are:

(1) Massive phosphate applications to reduce the need for future high phosphorus treatments (Younge and Plucknett, 1965, 1966).

(2) The use of silicates to satisfy the fixing capacity of soils (Ikawa, 1956; Bradfield, 1963) and to improve phosphorus solubility (Mahilum, 1965).

(3) Band placement of soluble phosphates to reduce their reaction with soils with high phosphorus fixation (Yaptenco, 1963).

(4) Application of lime to soils with high phosphorus fixing capacities to reduce iron and aluminum solubility (Fox *et al*, 1964).

(5) Selection of crops which will best utilize fixed phosphorus (Plucknett and Fox, 1965).

Interactions of Phosphates with Silicates

As early as 1906, Hall and Morrison indicated that the seat of the P-Si interactions was in the plant. In contrast, Fisher (1929) believed that the seat of the reaction was in the soil where the silicates improved the phosphorus availability. Recently, it was demonstrated by several investigators that both the plant and the soil were involved (Silva, 1971; Roy *et al*, 1971).

Although the ash content of many plants is predominantly opal, silicon is not considered an essential element. However, grasses and cereals (Clements, 1965(a); Okuda and Takahashi, 1965; Ayres, 1966; Yoshida *et al*, 1969) and other crops (Dewan and Hunter, 1949; Raleigh, 1953, DeDatta, 1958; Adlan, 1969; Thiagalingam, 1971) grow well in soils rich in available silicon. The first plant yield response to silicon in Hawaii was obtained in a pot study using sodium silicate (Sherman *et al*, 1955). In India DeDatta (1958) found that high applications of sodium silicate improved the yield and phosphorus status of berseem (*Medicago sativa*). The interest in silicate slags in Hawaii began in 1963 with experiments in which Sudan grass (*Sorghum sudanense*) was grown in a very phosphorus deficient Hydrandept (Suehisa *et al*, 1963; Monteith and Sherman, 1963). The benefits from silicates were reported to be due to improved phosphorus nutrition (Clements, 1965(b); Silva, 1971) and decreased aluminum toxicity (Jones and Handreck, 1967). Later, field trials on Kauai with sugar cane (*Saccharum officinarum*) demonstrated that the use of calcium silicate slags was commercially practical for sugar production (Clements, 1965(a); Ayres, 1966).

Crop responses to calcium silicate applications in Hawaii are generally reported on extremely weathered soils of the high rainfall regions. Such soils are characterized by low pH, low base saturation, low extractable silicon, and low silica-sesquioxide ratios (Silva, 1973), and much active alumina.

Effects of silicon are grouped into three categories: (1) an effect on soil fertility, (2) an effect on plant growth, and (3) an effect on the resistance of plants to insects and diseases.

Effects on Soil Fertility: Research from Hawaii and elsewhere suggests the following benefits from applying calcium silicates:

(1) increased solubility of soil phosphorus,
(2) decreased fertilizer phosphorus fixation by soil,
(3) increased soil calcium and magnesium levels,
(4) increased soil pH,
(5) decreased concentrations of potentially toxic elements in the soil such as iron, aluminum, manganese, etc.,
(6) increased cation exchange capacity by increasing net negative charge, thus less leaching of nutrient cations,
(7) improved soil aeration and microbial growth.

The effects of silicates on soil fertility are reported to arise from an increase in phosphate anions by silicate anions (Tuilin, 1936; Toth, 1939; Batisse, 1946; Dean and Rubins, 1947; Batisse, 1950; Russell, 1973) or to improved soil aeration and microbial growth (Laws, 1950). Other investigators suggest that the release of phosphorus by silicon is not due to anion exchange, but possibly to an increase in pH (Raupach and Piper, 1959; Suehisa et al, 1963; Mahilum, 1965; Teranishi, 1968) or decrease in aluminum activity (Jones and Handreck, 1967) which prevent phosphorus precipitation.

Application of silicates has also been reported to decrease the phosphorus fixing capacity of many Hawaiian soils (Ikawa, 1956). Roy, et al (1971) have indicated that phosphorus desorption increases when silicates have been applied to some Hawaiian latasols. The effect of silicon on phosphorus desorption or fixation may be due to the interaction of silicon with sorption sites, or due to the inactivation of iron and aluminum by rendering them insoluble.

The use of silicates improves the efficiency of phosphorus fertilizers. Silicon exerts a solvent action on phosphorus fertilizers and thus renders the phosphorus in them more available. Suehisa et al (1963) studied P-Si interactions in three Hawaiian soils of different morphology and mineral composition. They found that Kapaa soil (low silicon) and Poamoho soil (high silicon) showed no beneficial responses when various soluble silicates were applied together with phosphates. However, Helemano soil (intermediate silicon) showed significant changes in yield and phosphorus uptake.

Effects on Plants: The following benefits from calcium silicate applications are reported on plants by many workers.

(1) improved phosphorus metabolism due to decreased phosphorus requirement within the plant,

(2) improved calcium nutrition,

(3) improved nutrient and enzyme balance,

(4) enhanced efficiency of water use by the plant,

(5) reduced accumulation of toxic concentrations of manganese or other elements in the plant,

(6) increased mechanical strength and decreased lodging,

(7) increased efficiency of the use of sunlight by plants,

(8) increased protection of plant tissue against insect damage and fungal diseases,

(9) improved seed set in some varieties of rice (*Oryzae sativa*).

Effects of silicon on plant growth are possibly related to reactions of this element with phosphorus in the soil and in the plant (Silva, 1971). This is attributed to the similarity between the two elements. The concentrations of phosphate and of water-soluble silicon in soils are rather closely linked since their solubilities are controlled by aluminum hydroxide and sesquioxide surfaces. Engel (1958) suggested the possibility of antagonism between silicon and phosphorus in culture solutions, and showed that wheat plants took up less silicon in the presence of phosphorus. Silicon in the rice plant was shown to inhibit the luxury consumption of phosphorus (Okuda and Takahashi, 1962). Conversely, many investigators reported significant increases in crop yield and total phosphorus uptake due to silicate applications (Suehisa, et al, 1963; Monteith and Sherman, 1963; Hunter, 1965; Thiagalingam, 1971). Roy et al (1971) reported that application of phosphates increased the solubility of silicates.

Silicates have been reported to increase phosphorus assimilation by Sudan grass in Humic Latosols (Sherman et al, 1955). Silva (1971) presented evidence which strongly suggested that silicon has a role in phosphorus metabolism. Silicon may improve distribution of manganese in plants (Williams and Vlamis, 1957; Vlamis and Williams, 1967) or reduce its uptake (Clements, 1965(b)) and hence counter its adverse effects within the plant.

Effects on Resistance to Pests and Diseases: An adequate supply of silica allows the element to be deposited on the cell walls of plants rendering them more resistant to penetration by both insects and fungus. Wagnor (1940) reported that an adequate silicon content might increase the resistance of some cereals to powdery mildew (*Erysiphe graminis*). Rice plants receiving adequate silicon showed resistance to sesame spot disease (*Cercospora sesami*) and rice blast (*Pyricularica oryzae*) (Takijima et al, 1949; Volk et al, 1958), and to the stem borer *Chilo suppressalis*

(Djamin and Pathak, 1967). An adequate supply of silicon also increased the resistance of wheat (*Triticum aestivum*) to hessian fly (*Mayetiola destructor*) (Miller *et al*, 1960) and of sorghum (*Sorghum bicolor*) to central shoot fly (*Atherigone indica*) (Ponnaiya, 1951). An interesting relationship was demonstrated with sugar cane experiments between TVA slag applications and the disappearance of leaf freckle disease which was common to sugar cane growing in highly weathered soils (Clements, 1965(b)). In response to the slag treatments, the uptake of available soil manganese by the cane plants was decreased resulting in reduced incidence of the disease. Tamimi and Hunter (1970) reported that application of $CaSiO_3$ together with phosphorus reduced the level of infection by corn smut (*Ustilago maydis*).

Interactions of Phosphates with Aluminum

Al toxicity in acid soils is known to be a major cause of soil infertility (Kamprath, 1972). The element has been reported by numerous investigators to have toxic effects on plant growth (Dessureaux, 1969; Elliott *et al*, 1973), to inhibit Ca uptake (Schmehl *et al*, 1952; Johnson and Jackson, 1964) and to reduce P solubility and availability. High amounts of Al in soil favor the accumulation of P in roots which prevents their elongation and causes low yield as a result of induced P deficiency (Munns, 1965; Clarkson, 1966). The accumulation of Al in roots causes precipitation of P in the cell wall as $Al(OH)_2H_2PO_4$

which results in a reduction of the active uptake of P (Clarkson, 1967). Color photomicrographs of sections of barley roots (*Hordeum vulgare*) show a definite interaction of phosphate and aluminum in the root cap and 1 to 5 mm back from the root tip (McCormik and Borden, 1972). The P-Al interaction seems to be associated with the cell wall. Al accumulation in Sudan grass above about 120 ppm may depress phosphate uptake from P fertilizers (Fox *et al*, 1962).

Magistad (1925) related pH to the level of Al in soil and culture solutions, and reported that as pH increased, the level of Al in solution decreased rapidly to a minimal level ($<$ 1 ppm) at around pH 5 and above. However, Al in solution increased above pH 7. Fox *et al* (1962) reported that the level of $BaCl_2$-extractable Al was minimum in Hawaiian Latosols at pH 5.5 to 6.0. Similarly, Kamprath (1970) and Soares *et al* (1974) found KCl-extractable Al to be related to soil pH. However, the significance of KCl-extractable Al as an index to lime requirement of soils of the humid tropics has been questioned by Amedee and Peech (1976). Applications of lime to acid soils reduce soluble Al and increase P solubility and availability in the soil (Clements, 1962; Fox *et al*, 1962; Mahilum *et al*, 1970; Khalid, 1974). Exchangeable Al is replaced by Ca with the formation of $Al(OH)_3$. Increasing soil pH or adding P increased yield and P uptake of cotton grown in Al-containing nutrient solutions due to precipitation of Al (Foy and Brown, 1964). They suggested that a P/Al ratio greater than 2 is necessary to prevent an Al-induced P deficiency in nutrient solutions.

Phosphate Extraction Procedures

Inorganic phosphorus in soils occurs in various forms, i.e., water-soluble, acid soluble, alkaline soluble, adsorbed and lattice forms (Kurtz, 1953). Accordingly, many useful phosphate extraction procedures have been developed for different soils, some of which are:

Bray and Kurtz Method: This method was developed in Illinois by Bray and Kurtz (1945), following the work of Dickman and Bray (1941). They used ammonium fluoride (0.03N NH_4F) to remove adsorbed phosphates, and an acid reagent (0.025N HCl) to extract the calcium complexes. The method did not aim at accounting for all the soil phosphorus. Since rock phosphate did not dissolve in the solution employed, it was modified to contain 0.03N NH_4F and 0.1N HCl. The #2 solution dissolves rock phosphate and is suitable for highly weathered soils; while #1 solution is suitable for less weathered soils rich in calcium phosphate.

Truog Method: This method was developed by Truog (1930) for the acid soils of Wisconsin. The extractant is a 0.002N solution of sulfuric acid together with ammonium sulfate (3g/L). The aim is to adjust the acid concentration to approximately that of the root surface (Truog, 1930) and to provide SO_4^{-2} anions to exchange with PO_4^{-3} anions in the soil complex. A large volume of solution per gram of soil is used (1g soil/200 ml solution).

Modified Truog Procedure: This method was developed by Ayres and Hagihara (1952) for the highly weathered lateritic soils of Hawaii. The authors found that the acid concentration of the Truog method (Truog, 1930) was too low for some of the more highly weathered lateritic soils of Hawaii. As a result they increased the acid concentration tenfold. Another departure from the Truog method was the addition of a small amount of activated carbon (Darco G-60) to the soil-extractant mixture prior to shaking to remove organic matter which might interfere with the subsequent determination of phosphorus. The ratio of soil to extractant was also increased from 1:200 to 1:100.

Olsen Method: The Olsen or sodium bicarbonate method was developed by Olsen *et al* (1954) in Colorado for calcareous soils. The method may be applicable to acid and neutral soils as well as to calcareous soils. The main effect of $NaHCO_3$ in calcareous soils is to decrease the Ca^{++} ion activity, which in turn increases phosphorus solubility. The same thing happens in acid and neutral soils where the solubility of calcium phosphates increases due to the suppression of Ca^{++} ion activity by $NaHCO_3$ (Olsen _et al_, 1954). The HCO_3^- ion replaces the phosphate adsorbed on the surface of soil particles (Kurtz, 1953; Olsen _et al_, 1954). The method employs extraction of the soil for 30 minutes with a 0.5_M_ $NaHCO_3$ solution adjusted to pH 8.5 with NaOH. The soil:solution ratio is 1:20 (5 g of soil and 100 ml of the $NaHCO_3$ solution).

The phosphate extraction procedures mentioned above measure some form of soil phosphorus and when calibrated can predict whether the soil is deficient in phosphorus. However, they do not indicate how much phosphate is required to bring a soil to a prescribed level of phosphate nutrition (Fox _et al_, 1968; Fox and Kamprath, 1970). When the extractant is sufficiently acid, the phosphorus extracted will be proportional to the labile phosphate pool (capacity factor). If the soil is not too acid, the phosphorus extracted indicates the level of phosphate in the soil solution (intensity factor). Extraction of soils of varying properties with the same solution will lead to anamolous results.

The phosphate extracted by 0.02_N_ H_2SO_4 indicates the intensity of phosphorus nutrition, i.e., the level of phosphate in the soil solution. However, this extractant can dissolve some forms of insoluble phosphate, and thus extract phosphate not presently available to plants. This is why the modified Truog method is not recommended for soils containing rock phosphate (HSPA, 1963, 1966, 1967).

The sodium bicarbonate extractant is more suitable than the modified Truog extractant for determining available phosphate in soils that have received rock phosphate (HSPA, 1967). In several sugar cane plantation field experiments where soil phosphorus was shown to be adequate by the modified Truog method, but deficient by the sodium bicarbonate method, phosphate applications resulted in significant sugar yield gains (HSPA, 1967). The sodium bicarbonate method is also suitable for calcareous soils since the extractant does not react with carbonates. Ozanne and Shaw (1968) found that the sodium bicarbonate soluble phosphate varied widely in soils of different buffering capacities.

Phosphorus Sorption Curves

The recently developed phosphate sorption curve method for determining the phosphorus requirement of soils has many advantages over soil phosphorus extraction methods (Ozanne and Shaw, 1968). When values of phosphate sorbed are plotted against the log of phosphorus remaining in the soil solution, an approximately linear relationship is obtained (Ozanne and Shaw, 1968). The slope of the curve describes the quantity/intensity relationship, or the phosphorus buffering capacity of the soil, and gives a measure of the quantity of phosphate which must be added to raise the intensity one unit. The intercept at zero phosphate sorption gives information about the present phosphate status of the soil. The amount of phosphate needed to bring the soil to various levels of adequacy for crop production are read directly from the graph.

Phosphate sorption curves have been developed by Fox et al (1968) to estimate phosphate requirements of Hawaiian latosols and to evaluate residual effects of phosphate fertilizers. The method by Fox and Kamprath (1970) consists of equilibrating 3-g. samples of soil (oven-dry basis) in 30 ml of 0.01 M $CaCl_2$ containing graded amounts of $Ca(H_2PO_4)_2$ for 6 days at 25°C. Three drops of toluene are added to retard microbial activity. The samples are shaken for 30 minutes twice a day. After equilibration, the samples are centrifuged and phosphorus is determined in the clear supernatant. The phosphate which has disappeared from the solution (sorbed P) is plotted against P in the supernatant solution to obtain P sorption curves.

The concentration of phosphate required in soil solution for maximum plant growth (external P requirement) varies with different crops. Beckwith (1965) suggested 0.2 ppm P as the value at which most agricultural plants attain near maximum growth. Asher and Loneragan (1967) found that some plants required as little as 0.03 ppm P in the soil solution for maximum growth. In Australian soils, a value of 0.3 ppm P has been used as a standard value for determining fertilizer rates for wheat (Ozanne and Shaw, 1968). In a pot study 95 percent of maximum yield of millet (*Pennisetum typhoides*) was obtained when P in solution was adjusted to 0.2 ppm (Fox and Kamprath, 1970). In Hawaii 95 percent of maximum yield of corn was obtained when P in the soil solution was adjusted to 0.05 - 0.1 ppm (Fox *et al*, 1971). Soundararajan (1971) suggested 0.06 ppm P as a general value of adjusted solution P concentration for optimum growth of millet in many soils. The amount of phosphate in the soil solution required for maximum yield varies with soil moisture, since the diffusion of phosphates to plant roots is influenced by soil moisture content (Olsen and Watanabe, 1963, 1966).

Effect of Phosphorus on Growth and Yield of Crops

Phosphorus is an essential element for plant growth. It is a constituent of phospholipids, nucleic acid, and phytin. It has an important role in energy transfer reactions in the cell and carbohydrate breakdown and synthesis (Arnon, 1953). A good supply of phosphorus early in the life of the plant is important in laying down the primordia for reproductive parts and for adequate root growth. Phosphorus is associated with early maturity of cereals, and is essential for seed formation. If other factors are not limiting, the growth of plants will be proportional to the amount of phosphorus absorbed by the plant (Tisdale and Nelson, 1975). When phosphorus was not applied to the rice plant, Patrick and Mahapatra (1968) observed the following symptoms: (a) reduced tillering; (b) restricted root development; (c) delayed maturity; (d) impaired nutrition of other nutrients; and (e) inhibited plant growth. Application of phosphate fertilizers to Hawaii soils increased the yield of taro (*Colocasia esulenta*) (dela Pena and Plucknett, 1967), sugar cane (Rosenau, 1969), papaya (*Carica papaya*) (Adlan, 1969), banana (*Musa spp*) (Warner *et al*, 1972), tomato (*Lycopersicon esculentum*) (Kratky and Tamimi, 1974). Application of phosphates also resulted in high beef production on Kikuyugrass (*Pennesitum clandestinum*) (Tamimi *et al*, 1968).

Plant Uptake of Phosphates

The uptake of phosphates by plants from the soil is influenced by three parameters: (a) the capacity factor which refers to the amount of phosphate ion in the solid phase: (b) the intensity factor which indicates the quantity of phosphate in the soil solution, and (c) the rate factor which shows the rate of movement of phosphate in the soil. The supply of phosphate to the plant can be diagramed as follows:

$$\text{P soil} \underset{R_2}{\overset{R_1}{\rightleftharpoons}} \text{P solution (near root surface)}$$

$$\downarrow$$

$$\text{diffusion}$$

$$\downarrow$$

$$\text{P solution (near root)} \underset{R_4}{\overset{R_3}{\rightleftharpoons}} \text{P plant}$$

Since phosphate ions are relatively immobile in soil, they have a narrow root-surface sorption zone (Barber, 1963) and they move predominantly by diffusion (Olsen and Watanabe, 1963; Olsen and Kemper, 1968) . The diffusion rate of phosphate in Hawaiian soils was first measured by Lai and Mortland (1962) and was found to estimate the rate factor influencing phosphate uptake. At low phosphate saturation, phosphate will be held tightly by the soil, the rate of desorption will be low, the concentration of phosphate in the soil solution at equilibrium will be low, and consequently, the diffusion rate will be slow. On the other hand, at high phosphate saturation the phosphate will be more loosely held, desorption will be higher and the resulting higher concentration in the soil solution will lead to a higher rate of diffusion. The importance of phosphate percentage saturation in determining phosphate uptake by plants has been demonstrated by many investigators (Williams, 1960; Williams and Knight, 1963; Woodruff and Kamprath, 1965).

A radioactive tracer technique developed to measure phosphate uptake showed that phosphate uptake by plants varied greatly among soils (Lai and Okazaki, 1970). The total amount of phosphate absorbed by plants is the product of crop yield (oven-dry basis) and composition (Dean and Fried, 1953).

Increasing Phosphorus Availability

Phosphorus availability to plants in tropical soils varies with morphological properties of the soil, previous management, fertilizer solubility, granule size and placement (Suehisa *et al*, 1955; Olson and Engelstad, 1972). Other factors which affect phosphorus availability to plants include soil pH, presence of anions such as silicates and sulfates, soil micro-organisms and organic matter (Norman, 1961).

It is widely accepted that plants respond differently to different sources of phosphorous depending on the phosphorus fixing capacity of the soil (McLean and Logan, 1970). This suggests that there may be a best source of phosphorus for a given soil condition.

Rock phosphate is the primary raw material for producing fertilizer phosphorus. However, its solubility is low in most soils except those that are very acid. The availability of phosphorus in rock phosphate can be increased by many ways.

Increasing P Availability by Increasing Solubility:

The amount of water-soluble phosphate in fertilizer is a good measure of the availability of fertilizer phosphorus to plants (Tisdale and Nelson, 1975). Yield and phosphorus availability increase with increased water solubility of phosphorus fertilizers (Lawton et al, 1956). The same investigators state that for maximum crop production, phosphorus materials should contain not less than 40 percent of their phosphorus in water-soluble form. The water solubility of phosphorus in a fertilizer material can be increased by two methods:

(a) Defluorination of Rock Phosphate: This refers to the processes by which natural phosphates are heated to high temperatures in the presence of silica and water vapor to volatilize fluorine and convert phosphorus into more available forms, mainly alpha tricalcium phosphate (Jacob, 1951). The product of defluorination has been referred to as calcined phosphate (Jacob, 1944), alpha tricalcium phosphate (Jacob, 1951), fused phosphate rock and fused tricalcium phosphate (Hignett and Hubbuch, 1946; Jacob, 1951).

The products of rock phosphate defluorination differ in percent phosphorus and fluorine content according to the type of process followed (Hignett and Hubbuch, 1946;

Whitney and Hollingsworth, 1949; Jacob, 1944; Jones and Rogers, 1949; Rogers et al, 1953; Webb et al, 1961(a)). Defluorination is brought about by calcination or fusion of rock phosphate. Calcination refers to the heating of rock phosphate with silica and water vapor to temperatures below the melting point of the mix (Jacob, 1944; Jones and Rogers, 1949; Rogers et al, 1953; Webb et al, 1961(a)). Defluorination is brought about by calcination or fusion of rock phosphate. Calcination refers to the heating of rock phosphate with silica and water vapor to temperatures below the melting point of the mix (Jacob, 1944; Jones and Rogers, 1949). On the other hand fusion is the process in which rock phosphate is heated in the presence of silica and steam to temperatures above the melting point of the mix so that the furnace charge will fuse to form a glassy product (Jones and Rogers, 1949; Rogers et al, 1953).

(b) Acidulation of rock phosphate: As early as 1843 Sir John Lawes of Rothamsted discovered that a more available form of phosphorus could be obtained by treating rock phosphate with sulfuric acid. Treatment of rock phosphate with sulfuric acid or phosphoric acid to produce ordinary or treble superphosphates, respectively, is called acidulation (Jones and Rogers, 1949; McLean et al, 1965).

Rock phosphate partially acidulated with phosphoric acid is better than completely acidulated rock phosphate for high phosphorus fixing soils. Crop yields increase steadily with increasing degree of acidulation up to 20 percent and then level off or decline with further acidulation. This is because the relative amounts of phosphorus fixed are higher with a higher degree of acidulation (McLean and Logan, 1970). Soils with moderately high fixation yield best with partial acidulation (20 percent); soils with low fixation yield best with complete acidulation (superphosphate); and soils with intermediate fixation yield equally well with either form (McLean and Logan, 1970).

Fertilizer laws generally discourage the use of partially acidulated fertilizers because they don't give credit for total P_2O_5. In order to protect the consumer, these laws require that only the "available" form of phosphate be identified on the fertilizer. Available P refers to water-plus citrate-soluble P.

Complete acidulation of rock phosphate for high phosphorus fixing soils is paradoxical: (1) The first 20 percent increment of phosphoric acid solubilizes more than ten times as much phosphorus in the rock phosphate as the last 20 percent; (2) each unit of phosphorus in phosphoric acid is about three times as costly as one in rock phosphate; (3) the partially acidulated material has a better residual effect than superphosphate (McLean and Wheeler, 1964; McLean and Balam, 1967; Fox et al, 1968).

Increasing Availability by Decreasing Fixation: In soils with high phosphorus fixing tendencies, highly soluble phosphates (water soluble phosphates) are subject to rapid fixation. The availability of phosphorus in a fertilizer material can be enhanced by decreasing the possibility of fixation. This can be achieved by (a) granulation of the fertilizer material; (b) decreasing water solubility; (c) banding; (d) pelleting; and (e) application of organic matter and soil amendments (Hardesty and Clark, 1951; Walthal and Bridger, 1943; Hill *et al*, 1948; Suehisa *et al*, 1955).

The production of phosphate fertilizers which are highly soluble in citrate, but insoluble in water, is a means to increase phosphorus availability in high phosphorus fixing soils, especially those of volcanic ash origin (FMP, 1971). Water-soluble phosphate fertilizers, such as treble superphosphate and ammonium phosphate are readily fixed by active alumina and iron in soil and become unavailable. Phosphate fertilizers which are very soluble in citrate, but insoluble in water can be produced by fusion of rock phosphate with olivine, serpentine, or a mixture of magnesia and silica (Walthal and Bridger, 1943; Hill *et al*, 1948; FMP, 1971). The original process was developed by Walthal and Bridger (1943) and involved fusing a mixture of rock phosphate and olivine in the ratio of 1:0.46 in an electric furnace. The product obtained was a glass containing 22.8 percent total P_2O_5, 94 percent of which was soluble in citrated ammonium nitrate solution. This material was produced in large scale under the name Thermo-Phos (Hill et al, 1948). Fusion of a mixture of rock phosphate, magnesia, and silica (1:0.28: 0.22), and quenching the melt in water result in a product with P_2O_5 completely soluble in citrated ammonium nitrate solution (Walthal and Bridger, 1943). Greenhouse tests on two soils (pH 6.0 and 6.3) indicated that the new product was as effective as ordinary and treble superphosphates (Walthal and Bridger, 1943; Hill _et al_, 1948; Jones and Rogers, 1949). Quenched material that only passes a 6-mesh screen gave lower plant response especially on calcareous soils. Field tests showed that this coarse material was inferior to superphosphate.

Fused magnesium phosphate is a commercial product produced in large scale in many countries (FMP, 1971). It is produced by smelting rock phosphate and magnesium silicate (serpentine or olivine) at 1400^oC and quenching the melt with water jets to give a sand-like product (FMP, 1971). If the melt is cooled slowly, crystals of apatite, $3Ca_3(PO_4)2.CaF_2$, and forstellite, $2MgO.SiO_2$, will form to decrease the citrate solubility. The P_2O_5 of the product is as effective as that of superphosphate (Walthal and Bridger, 1943; Hill _et al_, 1948), and the magnesium content should prove advantageous.

The process of producing fused magnesium phosphate or phosphate rock-magnesium silicate glass has many advantages (Walthal and Bridger, 1943):

(1) It does not require expensive elemental P, in contrast to processes for making metaphosphates.

(2) It does not require expensive acid, in contrast to processes for making superphosphates.

(3) It is not necessary to remove all the fluorine, in contrast to processes for making defluorinated rock phosphate.

(4) Addition agents needed to make the P_2O_5 soluble are inexpensive and required in small amounts.

(5) The final product contains soluble magnesia and silica. It is insoluble in water but it dissolves by direct contact with the plant roots in the soil.

Effect of Particle Size on P Availability

Granulation of superphosphate results in better physical condition of the carrier which is reflected in greater ease of application, less loss by dust on windy days and less caking in storage (Rogers et al, 1953). The agronomic value of granular versus powdered superphosphate has been studied by many investigators and it is generally accepted that phosphate fertilizers of relatively low solubility are more effective when finely ground and mixed with the soil rather than banded (Ayres and Hagihara, 1962; Webb et al, 1961(b)). This indicates that soluble materials such as superphosphate benefit more from granulation than less soluble materials (Skinner _et al_, 1941; Hardesty and Clark, 1951; Rogers _et al_, 1953). Granulated superphosphates applied broadcast generally give higher dry matter yield, furnish more phosphorus to plants and have better residual effects in acid soils than powdered materials (Berezova and Fodeeva, 1950; Vishinsky, 1950).

Hardesty and Clark (1951) defined the particle size of a granular fertilizer as that which should "pass a No. 5 U.S. series sieve (4mm. openings) and be retained on a No. 18 sieve (1 mm. openings)." Rogers _et al_ (1951) stated that the 12 to 50 mesh (U.S. series) range was optimum for nitric phosphate fertilizers.

Phosphate fertilizers of relatively low solubility such as dicalcium phosphate, calcium metaphosphate, fused tricalcium phosphate, fused magnesium phosphate and raw rock phosphate are most effective when they are in a finely ground form (Whittaker, 1947; Hill _et al_, 1948; Rogers,1951; Tisdale and Winters, 1953; Starostka _et al_, 1954). Hougland _et al_ (1942) found that finely ground calcined phosphate was nearly as effective as superphosphate on acid and neutral soils. A comparison of 10-mesh and 40-mesh fused tricalcium phosphate showed that phosphorus of the 40-mesh material was somewhat more available than that of the 10-mesh. On the other hand, growth was significantly better with the 40-mesh than with the 10-mesh material on low fixing soils and about the same on high fixing soils

(Neller and Bartlett, 1957). A similar study carried out by Terman (1944) showed relative increases of 95 percent for coarse material and 102 percent for finer material compared to treble superphosphate. Long and Winter (1951) showed that when fused tricalcium phosphate was ground to pass a 40-mesh sieve, it compared favorably with superphosphate in extremely phosphorus deficient soils. Joos and Black (1950) compared three sizes of rock phosphate: commercial (87 percent passed through 300-mesh), 150- to 300-mesh, and 400-mesh. The order of decreasing phosphorus availability of the various sizes was 400-mesh, commercial and 150- to 300-mesh. This indicates that the surface of rock phosphate has a role in phosphorus availability. Most of the commercial raw rock phosphate fertilizers are ground so that 90 percent or more will pass a 100-mesh sieve (Rogers et al, 1953). In some cases particles finer than those found in the commercial product had increased availability to plants, but this did not appear to justify the cost of grinding rock phosphate finer than the commercial product. A comparison of different phosphate rock-magnesium silicate glasses showed that coarse glass was inferior to finely-ground glass (Hill et al, 1948). The authors added that a particle size smaller than 60-mesh was necessary for favorable comparison of the glass with treble superphosphate. This is attributed to the effect of particle size on citrate solubility of the glass. Citrate solubilities of glass with particle size of 60- and 300-mesh are 52.8 and 86.8 percent, respectively (Hill *et al*, 1948).

Effect of pH on the Availability of Fertilizer Phosphorus

It is generally accepted that phosphate rock is a more effective source of phosphorus for plants on acid soils than on neutral or alkaline soils because the solubility of phosphate rock is relatively high at pH 4.6 to 5.6 but is low at pH 6.6 (Joos and Black, 1950). Ayres and Hagihara (1961) found that the availability of raw rock phosphate was inversely related to soil pH as well as to the level of exchangeable calcium and the degree of calcium saturation. Soil acidity developed by plant roots and soil microbes can react with phosphate and other mineral fragments to convert their phosphorus into available forms (Graham, 1955). Ellis *et al* (1955 stated that a pH of 6.0 or lower appeared to be necessary for satisfactory utilization of phosphate rock. However, superphosphate gave good yields at all pH levels tested.

Phosphorus fertilizers can also affect soil pH as superphosphate applied to soil was found to lower soil pH from 5.8 to 5.3, while fused tricalcium phosphate lowered pH from 5.8 to 5.5 (Neller and Bartlett, 1957).

Relative Efficiency of Different Phosphate Fertilizers

The efficiency of phosphate fertilizers in supplying phosphorus to crops is determined by many factors, some of which are: (a) type of crop, (b) percentage of the fertilizer phosphorus soluble in water, (c) particle size of the material, (d) method of ferilizer placement, and (e) certain soil properties, i.e., level of available soil phosphorus, soil texture, phosphorus fixing capacity, microbial activity, and so forth. It is widely accepted that in soils with high phosphorus fixing capacities, phosphorus sources differ in the availability of this nutrient to plants (Stanford and Nelson, 1949; Lawton et al, 1956; Raychaudhuri, 1963; McLean and Logan, 1970; Novoa and Nunez, 1974). This is reflected in the amount of phosphorus absorbed, the yield of plant material and the variation in behavior of the P source over a period of time (Kurtz, 1953; Novoa and Nunez, 1974).

Increased water solubility of phosphate fertilizers results in increased phosphorus availability to plants as well as increased yields (Lawton et al, 1956; Webb et al, 1961(a), 1961(b); Mclean and Logan, 1970; Singh et al, 1976). Lawton et al (1956) stated that when granular phosphorus fertilizers were mixed well with the soil, the uptake of phosphorus was positively related to the percentage of water-soluble phosphorus in the materials. Singh et al (1976) found that yields of wheat, paddy and berseem on neutral to alkaline soils were closely related to the water solubility of the phsophorus fraction in three nitric phosphates which differred in water solubility of their phosphorus fraction. Phosphorus sources with varying water-solubilities may give the same dry matter yield, but different plant phosphorus concentrations (Stanford and Nelson, 1949).

The method of placement of phosphates is more important than water solubility, especially on acid soils (Webb et al, 1961(a)). Webb and Pesek (1958) found no advantage from increased water solubility when fertilizer phosphorus was applied broadcast and plowed under. Ayres and Hagihara (1961) found that when raw rock phosphate and superphosphate were mixed with acid soil, yields were the same. However, banded superphosphate was superior to banded raw rock phosphate and mixed raw rock phosphate was superior to banded superphospahte.

In acid soils phosphate materials which are comparatively less water soluble are as effective as superphosphates since acid soils fix water-soluble phosphorus in forms unavailable to plants (Kanwar and Grewal, 1958; Raychaudhuri, 1963; Goswami et al, 1971).

Experience indicates that superphosphate can be used effectively as a source of phosphorus for plants regardless of the soil involved (Joos and Black, 1950; Cooke, 1956). Treble superphosphate applied broadcast was found superior to nitric phosphates with 30 and 50 percent water-soluble phosphate (Singh et al, 1976). Superphosphate was superior to phosphate rock-magnesium silicate glasses in very acid (pH $<$ 5.5) and acid (pH 5.5 - 6.5) soils and greatly superior in neutral soils (pH $>$ 6.5) (Cooke, 1956). The phosphorus fixing capacity of the soil determines the effectiveness of the phosphorus source. McLean and Logan (1970) found that the phosphorus content of corn seedlings increased in direct proportion to the degree of water-solubility of "available" phosphorus in low fixing soils and decreased with increased water solubility in high fixing soils. In soils with high phosphorus fixing capacity treble superphosphate gave yield increases in the initial stages of growth. However, after 50 days of growth, the controlled release fertilizer, magnesium ammonium potassium phosphate, was more effective in supplying phosphorus (Novoa and Nunez, 1974). In soils with low phosphorus fixing capacity, various sources of phosphorus behave similarly, however, superphosphate is superior in the early stages of growth (Novoa and Nunex, 1974).

Phosphate rock-magnesium silicate glasses as well as other high temperature silicophosphates are more soluble in acid than neutral conditions, so tend to be of more value in acid than neutral or calcareous soils. They are of more value to crops adapted to taking their phosphate from diluted rather than concentrated solutions (Cooke, 1956). Silicophosphates are inferior to superphosphate in all soils (Cooke, 1956). But when they are finely ground, they compare favorably with superphosphate in acid soils, but not in calcareous soils (Hill _et al_, 1948).

Materials and Methods

Description of Soils

The soils used in this study were the Halii and the Lualualei series. These soils represent contrasting phosphorus fixing tendencies as well as physical, chemical and mineralogical composition (Tables 1 and 2). They have been described by Cline *et al* (1955), USDA Soil Taxonomy (1972) and McCall (1973).

Halii Soil: This soil was brought from the Kauai Branch Station at Kapaa on the island of Kauai. It is a member of the clayey, ferritic, isothermic family of Typic Gibbsihumox. This soil developed from material weathered from basic igneous rock and volcanic ash. It is found at elevations ranging from 90 to 300 meters, it has an annual rainfall of 250 to 500 cm and its mean annual soil temperature is 22^{o}C (71^{o}F). The soil is dark brown with a granular structure. It is made up of 20 percent or more gravel-size aggregates that are 30 percent or more gibbsite ($Al_2O_3.3H_2O$). The main constituents of the surface layer are iron and aluminum oxide as bases and silica have been leached out due to the intensive weathering. The surface layer has relatively high organic matter, low cation exchange capacity, low base saturation (less than 35 percent) and low pH. The soil has a high phosphorus fixing capacity and responds favorably to phosphate applications. It has good physical condition, however, its fertility status and

Table 1. Classification and some properties of Halii and Lualualei soils.[1]

Property	Soil Series: Halii	Soil Series: Lualualei
Order	Oxisols	Vertisols
Sub-group	Typic Gibbsihumox	Typic Chromusterts
Family	Clayey, ferritic, isothermic	Very fine, montmorillonitic, isohyperthermic
Important Secondary Minerals	Gibbsite, Goethite	Montmorillonite
Parent Material	Basalt	Alluvium
Annual Soil Temperature (^{o}C)	22	24
Rainfall (cm.)	250	50
Initial soil pH (Soil:Water, 1:1)	4.5	7.8
Organic Carbon Content	2.0	1.5
CEC (me/100 g)	27	50
Si (Water soluble, pmm)	0.7	4.7
Phosphate Adsorption Maxima (ugP/g soil)	2500	100
Fertilizer P for 0.2 ppm (Kg/ha)	2220	0

1. Data collected from various sources.

Table 2. Chemical analyses of Halii and Lualualei soils.

Soil	Ca[1]	Mg[1]	K[1]	P[2]	P[3]	Si[4]	Mn[1]	Cu[1]	Zn[1]	Fe[1]
	(me/100g)			(pmm)						
Halii	3.6	5.2	.3	30	6	.7	7	5	2	6
Lualualei	25.9	33.3	.5	60	20	4.7	9	5	1	2

1. 1<u>N</u> NH_4OAc pH 7.0

2. Modified Truog method

3. Olsen method

4. Water-soluble Si

water-holding capacity are poor. The Halii soil is used for sugar cane, pasture, wildlife habitat and water supply.

Lualualei Soil: This soil was collected from Kahe Point on the island of Oahu. It is a member of the very fine, montmorillonitic, isohyperthermic family of Typic Chromusterts. This soil developed from alluvium in areas with annual rainfall of 45 to 75 cm. It is found at elevations ranging from 3 to 38 meters. The mean annual soil temperature is 24^{o}C (75^{o}F). The Lualualei soil is very dark grayish-brown and contains montmorillonitic clays which are very sticky and very plastic when the soil is wet. When the soil dries, it cracks and forms huge blocks which disappear on re-wetting. The very sticky and very plastic nature of the clay makes cultivation difficult and practical only within a narrow range of moisture content. Furthermore, the presence of stones hinders machine cultivation. The soil has low organic matter, and relatively high cation exchange capacity and base saturation. Water penetration and root elongation are restricted, however, the soil has a high level of natural fertility. It is well supplied with phosphorus and rich in bases, especially with exchangeable magnesium. The pH of the surface layer is 7.0 to 8.0. This soil is used for sugar cane, pasture, truck crops, wildlife habitat and urban development.

Fertilizer Materials and Combinations

The fertilizer materials and treatment combinations used in this study are shown in Table 3. Amount of fertilizer materials added was based on manufacturer's analyses (Table 4).

Fused Magnesium Phosphate (FMP): The fused magnesium phosphate fertilizer was manufactured in Japan by the Fused Magnesium Phosphate Manufacturers' Association. It is made by fusion of rock phosphate with serpentine at 1400^{o}C and quenching the melt with water jets to give a sand-like product. The material is a glassy greenish-black sand with an average particle size of 0.2-1.5 mm. The larger granules dissolve more slowly in soil. Although the material is insoluble in water, its citric solubility is over 99 percent. Its components are gradually dissolved by the weak acid formed in soil and on the surface of the plant root.

The chemical analysis of fused magnesium phosphate is shown in Table 4. It contains PO_4 ions and short chains of silicate anions. The Mg and Ca ions are weakly bonded to the oxygen atoms.

Three P levels and three granule sizes of this material were used in the sutdy. The P levels were 100, 300 and 800 kg/ha for the Halii soil; and 50, 100 and 200 kg/ha for the Lualualei soil, plus a control for each soil (Table 3). The P levels were calculated on basis of Manufacturer's analysis. The granule sizes were normal size, NS (0.2 -

Table 3. Nutrient levels in the different fertilizer materials and combinations

Treatments		P (kg/ha	mg./kg. soil P	Si	Ca	Mg
Control		0	0	0	0	0
FMP:						
Halii	R_1	100	67	71	164	69
	R_2	300	200	214	492	207
	R_3	800	533	570	1311	552
Lualualei	R_1	50	33	36	82	35
	R_2	100	67	71	164	69
	R_3	200	133	142	328	138
TSP:						
Halii	R_1	100	67		44	
	R_2	300	200		133	
	R_3	800	533		355	
Lualualei	R_1	50	33		22	
	R_2	100	67		44	
	R_3	200	133		88	
TSP + $CaSiO_3$:						
Halii	R_1	100	67	71	146	
	R_2	300	200	214	439	
	R_3	800	533	570	1170	
TSP + $MgSO_4.7H_2O$						
Halii	R_2	300	200		133	50

R_1, R_2, R_3 refer to rates of phosphorus

Table 4. Manufacturer's and laboratory chemical analyses of treble superphosphate and different granule sizes of fused magnesium phosphate.

Type of P Fertilizer	P %	Ca %	Mg %	SiO_2 % [2]	TOTAL %
TSP[1]	20.0	13.3	--	--	33.3
FMP(NS)[1]	8.7	21.3	9.0	20.0	59.0
FMP(NS)[2]	9.4				
FMP(C.F.)[2]	10.0				
FMP(F.F.)[2]	9.4				

1 Manufacturer's chemical analysis

2 Laboratory analysis of total P with aqua regia

1.5 mm), coarse fraction, CF ($\geq$0.495 mm) and fine fraction, FF ($<$0.495mm). The coarse and fine fractions were separated with 32-mesh U.S. standard sieve. Treatments applied to the Halii soil included the three particle sizes, while only the normal size treatments were applied to the Lualualei soil.

Treble Superphosphate (TSP): Treble superphosphate is produced by treating rock phosphate with phosphoric acid. It contains 46 percent P_2O_5 (20 percent P) of which 95 percent is water-soluble, and 100 percent is classified as "available." The material contains 18.6 percent CaO (13.3 percent Ca) and trace amounts of sulfur(1 percent). This granular material was manufactured by Brewer Chemical Co. in Hawaii.

Three P levels of the regular granule size were applied to each soil, i.e., 100, 300 and 800 kg/ha for the Halii soil and 50, 100 and 200 kg/ha for the Lualualei soil (Table 3).

Treble Superphosphate with $CaSiO_3$: This treatment was selected to compare the possible effect of Si in FMP with the same amount of Si added as $CaSiO_3$ to Treble Superphosphate. This fertilizer combination was applied only to the Halii Soil.

Treble Superphosphate with $MgSO_4$: The possible effect of Mg in FMP was evaluated by comparing FMP with TSP containing 50 ppm Mg as $MgSO_4.7H_2O$. This rate of Mg is lower than that in the comparable FMP treatment (207 ppm Mg) because $MgSO_4.7H_2O$ is relatively more soluble than FMP and Mg toxicity might occur at higher rates of Mg. Only one Mg treatment was utilized on the Halii soil to get a preliminary assessment of the Mg in FMP.

Blanket Fertilizer Application: The uniform fertilizer treatment given to both soils included:

400 kgN/ha as urea, $CO(NH_2)_2$;

300 kgK/ha as KCl;

10 ppm Zn as $ZnSO_4.7H_2O$; and

1 ppm B as H_3BO_3.

Immediately after harvesting the plant crop 600 kgN/ha and 300 kgK/ha were added for the subsequent ratoon crop.

Description of Study

The study was carried out in the University of Hawaii greenhouses at the Mauka Campus. Halii and Lualualei soils were sieved with a 10-mesh U.S. sieve and left in the open overnight to dry. The moisture content of each soil was determined. One gallon tin cans lined with black plastic were used for the investigation. The fertilizer treatments were added on the basis of the oven-dry weight of each soil.

Plan of Experiment

The experimental layout in the greenhouse was a randomized complete block design with three replicates.

Twenty treatments were applied to the Halii soil and eight to the Lualualei soil.

Cultural Practices

Sudax (*Sorghum bicolor* x *S. sudanense*) was used as the indicator plant. A germination test carried out in the laboratory showed that the seeds had a germination percentage of 76. Twenty seeds per pot were planted 1/2 inch deep on June 3, 1975, and the soil was watered immediately to wet the whole profile. Plants were watered daily until the rate of evapotranspiration increased to the point where they had to be watered twice a day. After two weeks plants were thinned to ten per pot. Thinning was done by removing the smallest and the longest plants leaving the most uniform ten plants in each pot. The thinned plants were cut into small pieces and added to the pot from which they were thinned so that nutrients they contained would be returned to the pot. Plant and first ratoon crops were harvested when they were each five weeks old (July 12, and August 20, respectively). At harvest plants were cut 1 inch above the soil, placed in paper bags and dried at 70^{o}C for 48 hours. The oven-dry weight of the sample (ten plants) was expressed as dry matter yield in grams per pot.

Plant Analysis

The entire plants of each sample were ground in a stainless steel Wiley mill and analyzed with the quantometer for P, Si, Mg, Ca, K, and Mn.

Soil Analysis

After harvest of the ratoon crop, the soil in each pot was mixed thoroughly, sieved (20-mesh) and a suitable sample taken. Samples from all treatments were analyzed for 0.5M $NaHCO_3$-extractable P, modified Truog-extractable P, water-extractable Si, and 1N NH_4OAc-extractable Mg, Ca, K,Fe,Zn, Cu and Mn. Samples from the Halii soil were also analyzed for 1N KCl-extractable Al.

Details of the methods of extraction and determination are shown in Appendix A.

Soil pH: pH of soil samples was determined in a 1:1 soil-water suspension and a 1:1 soil-KCl (1N KCl) solution suspension after an hour of equilibration using a Beckman Digital pH meter.

Statistical Analysis

Dry matter yields, plant analyses and soil analyses data was analyzed by analysis of variance using the Factorial-Split Plot Analysis Program. Statistical significance of treatment mean differences was tested with the Bayes Least Significance Difference Test (BLDS). Graphs were drawn by the EZPLOT program using a CalComp 566 eleven inch drum plotter. All the above mentioned programs were available at the University of Hawaii Computer Center.

RESULTS AND DISCUSSION

The effect of rate and source of fertilizer P applied to Halii and Lualualei soils and the effect of granule size of fused magnesium phosphate applied to the Halii soil on dry matter yield, nutrients concentration, nutrient uptake and soil composition will be discussed.

Dry Matter Yield

The dry matter yield of plant and ratoon crops of Sudax increased with increasing amount of FMP(NS), TSP and TSP+Si applied to the Halii soil (Figure 1, Appendix Table 1) and FMP(NS) and TSP applied to the Lualualei soil (Figure 2, Appendix Table 2). When no fertilizer P treatments were compared, dry matter yields were much higher in the Lualualei soil than in the Halii soil. In addition the maximum yields obtained in the Halii soil with the application of 800 kgP/ha were lower than the maximum yields obtained in the Lualualei soil with the application of only 200 kgP/ha. This was attributed to the higher natural fertility of the Lualualei soil (Table 2).

In the Halii soil the highest dry matter yield in the plant crop was obtained with TSP + Si (109% of TSP) followed by TSP (100%) and finally FMP(NS) (90%). However, the yield differences between TSP with and without Si were not significant at the 5% level of probability. In the Lualualei soil the yield with FMP(NS) in the plant crop was 87% of the yield with TSP. The superiority of TSP over FMP

Figure 1. Variation in dry matter yield of Sudax with rate and source of P applied to the Halii soil

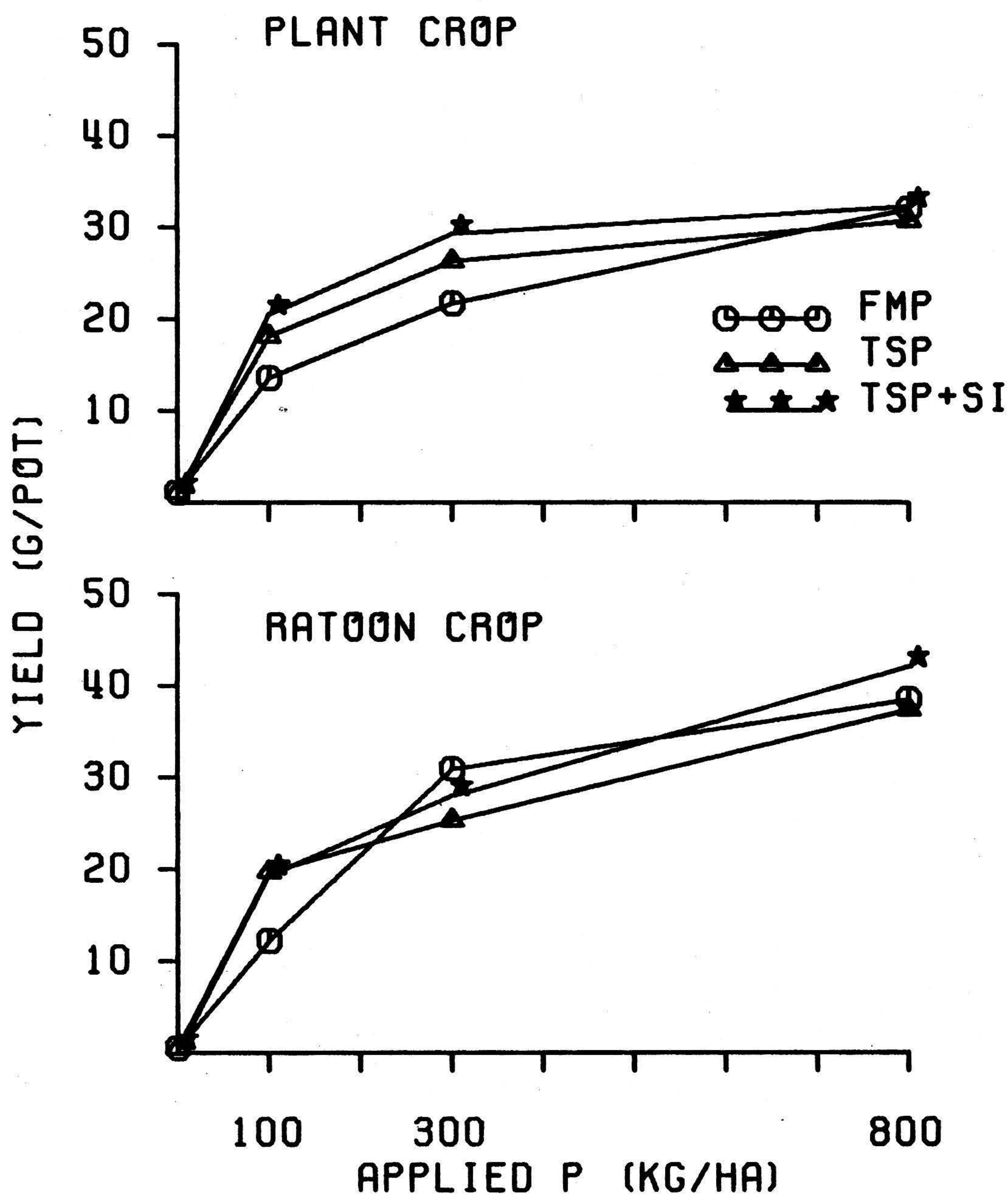
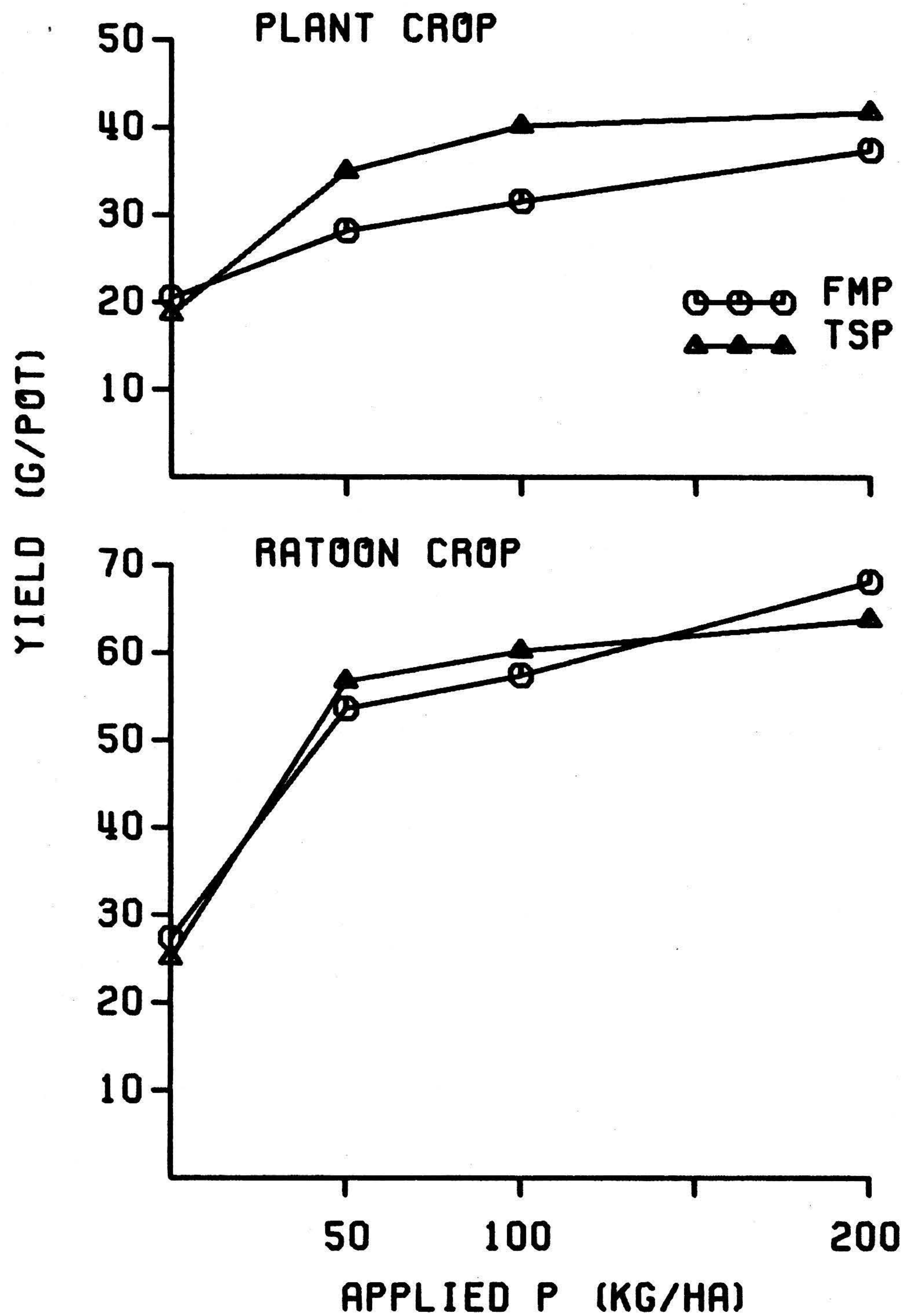

PLANT CROP
FMP
TSP
TSP+SI
RATOON CROP
YIELD (G/POT)
50
40
30
20
10
100
300
800
APPLIED P (KG/HA)

Figure 2. Variation in dry matter yield of Sudax with rate and source of P applied to the Lualualei soil


PLANT CROP
RATOON CROP
YIELD (G/POT)
50
40
30
20
10
70
60
50
40
30
20
10
FMP
TSP
50
100
200
APPLIED P (KG/HA)

in both soils was attributed to the high degree of water solubility of TSP. Fused magnesium phosphate (FMP, NS) is insoluble in water although its citric solubility is over 99%. When TSP was applied with calcium silicate to the Halii soil, the yield increased, but not significantly. The applied calcium silicate increased the soil Ca level and probably the availability of soil and fertilizer P. The influence of calcium silicate in increasing P availability has been reported by Sherman _et al_ (1955), King (1961), Monteith and Sherman (1963), Suehisa _et al_ (1963), Teranishi (1968), Adlan (1969), Rosenau (1969), Roy _et al_ (1971), Silva (1971) and Khalid (1974). Applications of calcium silicate were also found to increase extractable soil P and soil pH and to decrease soil Al. This will be discussed in the section on soil composition.

The dry matter yield of ratoon crops was the same with TSP and FMP(NS) in both soils (Figures 1 and 2; Appendix Tables 1 and 2). The low water solubility of FMP(NS) made it less subject to fixation, but its availability increased with time in the ratoon crop because its components were gradually dissolved by the weak acid formed in the soil and on the surface of well-established plant roots. On the other hand TSP was very subject to fixation because of its high water solubility. These phenomena resulted in the two materials giving nearly identical average yields in the ratoon crop in the Halii soil (compare 20.6 g/pot vs. 20.7 g/pot). Treble superphosphate applied with calcium silicate to the Halii soil gave higher average dry matter yield than TSP alone and FMP(NS) (compare 22.6 g/pot vs. 20.7 and 20.6 g/pot) probably because the added calcium silicate improved the availability of P and increased soil Ca levels. However, the increase was not significant as it was in the plant crop.

The pH levels of Halii and Lualualei soils (compare 4.5 vs. 7.8) had no or very little effect on the effectiveness of FMP. In the plant crop the yield with FMP(NS) was 90% of the yield with TSP in the Halii soil and 87% of the yield with TSP in the Lualualei soil. In ratoon crops FMP(NS) behaved similarly in both soils.

The TSP + Mg treatment applied to the Halii soil consisted of 300 kgP/ha together with 50 ppm Mg. This combination produced nearly the same yield as TSP in both plant and ratoon crops (Appendix Table 1). This suggested that the level of native Mg in the Halii soil was adequate for plant growth.

In both Halii and Lualualei soils the ratoon crop gave higher dry matter yields than the plant crop. This may be explained by the following points: (a) presence of well-established and efficient root-systems; (b) components of FMP, particularly P, became more soluble and hence more available to plants with time; (c) Si in FMP and $CaSiO_3$ became more soluble and hence more efficient in increasing

P availability to plants; (d) no competition with extra plants or weeds.

It should be pointed out that a significant source x rate of P interaction occurred in plant crops in both Halii and Lualualei soils but disappeared in ratoon crops (Tables 5 to 8). In the Halii soil the apparent source x rate of P interaction in the ratoon crop (Figure 1), which produced a larger source x rate mean square, was not shown to be significant largely because of its increased yield variability and the larger number of missing plots in the ratoon crop. In the Lualualei soil the apparent source x rate of P interaction in the ratoon crop (Figure 2) was not shown to be significant mainly because of its increased yield variability.

Significant dry matter yield responses to P applications have been obtained on the Halii soil in the plant crop of sugar cane (Teranishi, 1968) and corn (Thiagalingam, 1971). Responses to residual P applications on the Halii soil were obtained in the ratoon crops of sugar cane (Rosenau, 1969), and kikuyugrass and desmodium (Rashid, 1974). The latter responses were obtained only at high residual P rates.

The superiority of superphosphate over phosphate rock-magnesium silicate glasses in supplying P to plants has been reported in the literature in very acid (pH $<$ 5.5), acid (pH 5.5 - 6.5) and neutral soils (pH $>$ 6.5)

Table 5. Analysis of variance of dry matter yield and nutrient concentration of the plant crop of Sudax in Source x Rate of P experiment in the Halii soil.

Source of Variation	d.f.+	Yield	P	Mg	Si	Ca	K	Mn
		Mean Squares						
Replicates	2	4.82	0.00008	0.0001	0.010	0.001	.0003	529.86
Treatments	(11)	447.45**	0.00365**	0.0673**	0.287**	0.114**	.5600**	459.17
Source of P	2	41.60**	0.00001	0.0641**	0.599**	0.100*	0.2900**	543.36
Rate	3	1584.76**	0.01150**	0.1659**	0.486**	0.316**	1.4600**	500.67
Source x Rate	6	14.07*	0.00095**	0.0199*	0.083**	0.018**	.2000**	410.36
Error	19	5.86	0.00007	0.0025	0.013	0.002	.0400	566.58
Total	32							

\+ D.f. of error term = 22 - 3 = 19 because 3 observations were missing. D.f. of yield error term = 22

* Significant at 5% level

** Significant at 1% level

Table 6. Analysis of variance of dry matter yield and nutrient concentration of the ratoon crop of Sudax in Source x Rate of P experiment in the Halii soil.

Source of Variation	d.f.+	Yield	P	Mg	Si	Ca	K	Mn
		Mean Squares						
Replicates	2	8.54	.00004	0.010	.054	.041	.043	362.11
Treatments	(11)	688.62**	.00237**	0.077**	.229**	.113	.724	559.97
Source of P	2	15.76	.00270	0.054*	.288**	.054	.046	283.69
Rate	3	2461.23**	.00833**	0.157**	.576**	.334**	1.920*	1165.21*
Source x Rate	6	26.62	.00010	0.044*	.055*	.023	.352	349.44
Error	15	20.79	.00620	0.014	.020	.063	.404	281.52
Total	28							

\+ D.f. of error term = 22 - 7 = 15 because 7 observations were missing

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 7. Analysis of variance of dry matter yield and nutrient concentration of the plant crop of Sudax in Source x Rate of P experiment in the Lualualei soil.

Source of Variation	d.f.	Yield	P	Mg	Si	Ca	K	Mn
		Mean Squares						
Replicates	2	15.55	.0001	.0006	.0112	.0007	.0465	49.29*
Treatments	(7)	225.78**	.0012**	.0168**	.0377**	.0080	.6233**	137.43**
Source of P	1	119.17**	.0006*	.0003	.0216	.0007	.3902*	.17
Rate	3	455.27**	.0023**	.0385**	.0705**	.0183*	1.2561**	307.11**
Source x Rate	3	31.82*	.0002	.0006	.0103	.0002	.6829**	13.50
Error	14	7.73	.0001	.0007	.0052	.0043	.0496	11.91
Total	23							

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 8. Analysis of variance of dry matter yield and nutrient concentration of the ratoon crop of Sudax in Source x Rate of P experiment in the Lualualei soil.

Source of Variation	d.f.	Yield	P	Mg	Si	Ca	K	Mn
		Mean Squares						
Replicates	2	98.68**	.0005*	.006	.009	.0002	.026	6.540
Treatments	(7)	796.46**	.0008**	.044**	.065	.0114**	.496**	25.137
Source of P	1	.24	.0002	.003	.015	.0003	.004	2.042
Rate	3	1837.77**	.0016**	.094**	.086*	.0243**	1.146**	19.153
Source x Rate	3	20.56	.0002	.008	.061	.0024	.010	38.819
Error	14	10.84	.0001	.006	.025	.0013	.020	19.066
Total	23							

* Significant at the 5% level of probability

** Significant at the 1% level of probability

(Cooke, 1956). In both Halii (pH 4.5) and Lualualei (pH 7.8) soils TSP produced higher dry matter yields than FMP(NS) in the plant crop. However, in the ratoon crop the different sources of phosphorus behaved similarly in affecting yield. Similar results have been reported by Novoa and Nunez (1974) who found that after fifty days of growth, the controlled-release fertilizer, magnesium ammonium potassium phosphate, was more effective in supplying P than TSP.

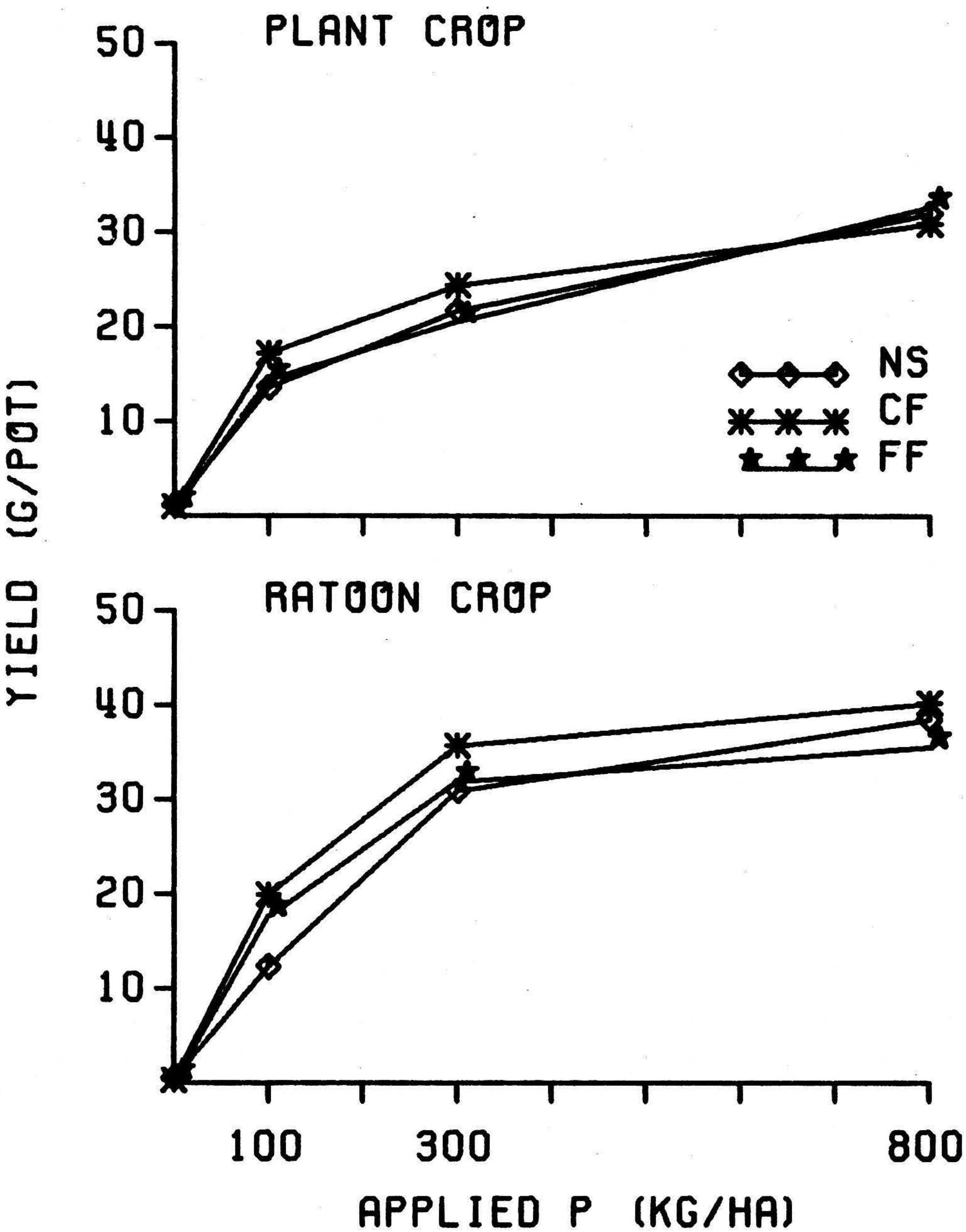
The three granule sizes of FMP (normal size, coarse fraction, fine fraction) applied to the Halii soil behaved similarly in affecting yield (Appendix Table 3). Although there was no significant difference (Bayesian Least Significant Difference Test) between the average yields produced by the three granule sizes in the plant as well as in the ratoon crop, the coarse fraction seemed to produce consistently higher yields than the normal size and the fine fraction (Figure 3). This may be due to the fact that the coarse fraction was less subject to fixation by the soil than the other two fractions and possibly also to the fact that the coarse fraction had a slightly higher total P than the other two fractions, although the difference was not significant (Table 4).

Nutrient Concentrations and Nutrient Uptake

Nutrient concentrations and total uptake of P, Mg, Si, Ca and K will be discussed in this section.

Plant P. In the plant crop in the Halii soil the three forms of P, namely FMP(NS), TSP and TSP+Si, tended to have

Figure 3. Variation in dry matter yield of Sudax with rate and granule size of FMP applied to the Halii soil



PLANT CROP
RATOON CROP
YIELD (G/POT)
APPLIED P (KG/HA)
NS
CF
FF
50
40
30
20
10
100
300
800

the same effect on plant P at lower and medium rates of P (100 and 300 kgP/ha). With the application of 800 kgP/ha, both TSP and TSP + Si resulted in a P concentration of 0.16% while FMP(NS) resulted in 0.12% (Appendix Table 4). This was attributed to the higher water solubility of TSP. In the ratoon crop FMP(NS) behaved similar to TSP and TSP + Si (Figure 4). This showed that FMP became more soluble with time. In the Lualualei soil applications of FMP(NS) and TSP resulted in similar plant P concentrations (Figure 5, Appendix Table 5). The ratoon crop tended to have lower P concentrations than the plant crop. This was most likely caused by dilution since dry matter yield of the ratoon crop was higher than in the plant crop.

In the Halii soil FMP(NS) gave the lowest average amount of P taken up by the plant crop followed by TSP and then TSP + Si (compare 18.9 mg/pot vs. 22.8 and 24.4 mg/pot) (Figure 6). The variation in average P uptake with TSP and TSP with Si was not significant (Appendix Table 6). In the ratoon crop average P uptake with FMP(NS) was more than average P uptake with TSP but less than that with TSP + Si (compare 27.4 mg/pot vs. 25.0 and 28.4 mg/pot). However, the differences were not significant at the 5% level of probability. In the Lualualei soil there was no difference in P uptake by both plant and ratoon crops due to P source. (Figure 7, Appendix Table 7).

Figure 4. Variation in plant P in Sudax with rate and source of P applied to the Halii soil

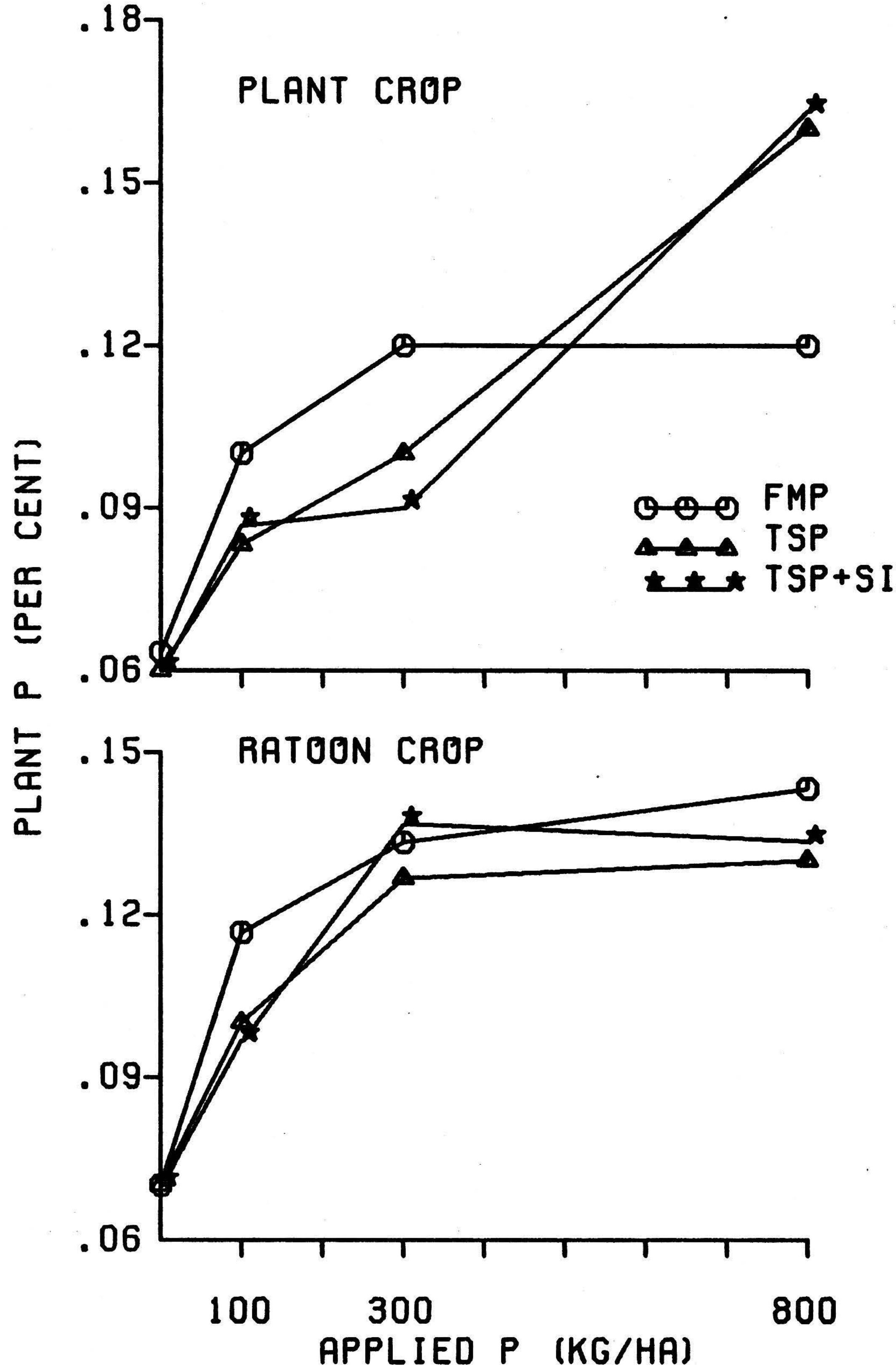

.18
.15
.12
.09
.06
PLANT CROP
FMP
TSP
TSP+SI
RATOON CROP
.15
.12
.09
.06
PLANT P (PER CENT)
100
300
800
APPLIED P (KG/HA)

Figure 5. Variation in plant P in Sudax with rate and source of P applied to the Lualualei soil

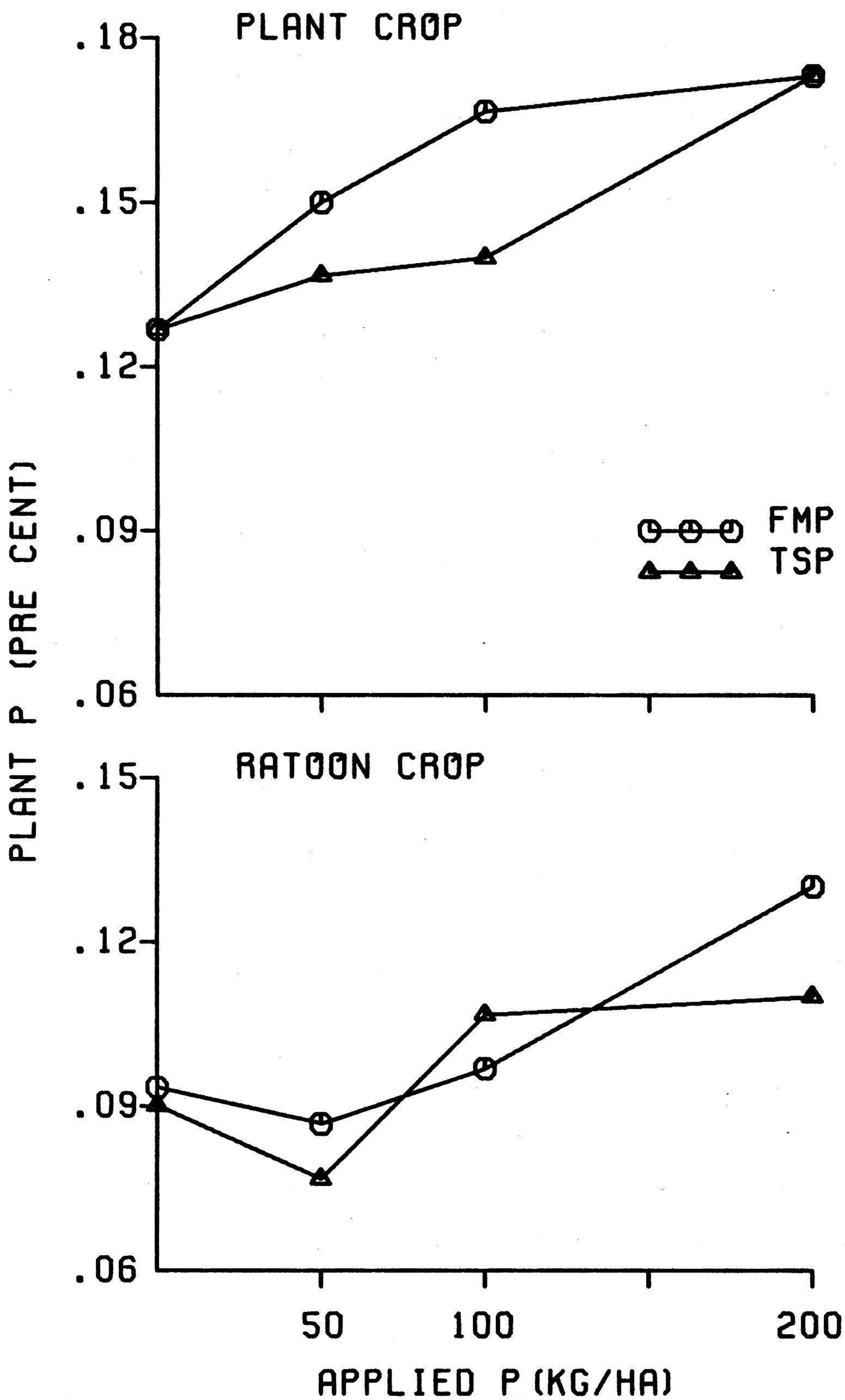

PLANT CROP
.18
.15
.12
.09
.06
FMP
TSP
PLANT P (PRE CENT)
RATOON CROP
.15
.12
.09
.06
50
100
200
APPLIED P (KG/HA)

Figure 6. Variation in P uptake by Sudax with rate and source of P applied to the Halii soil

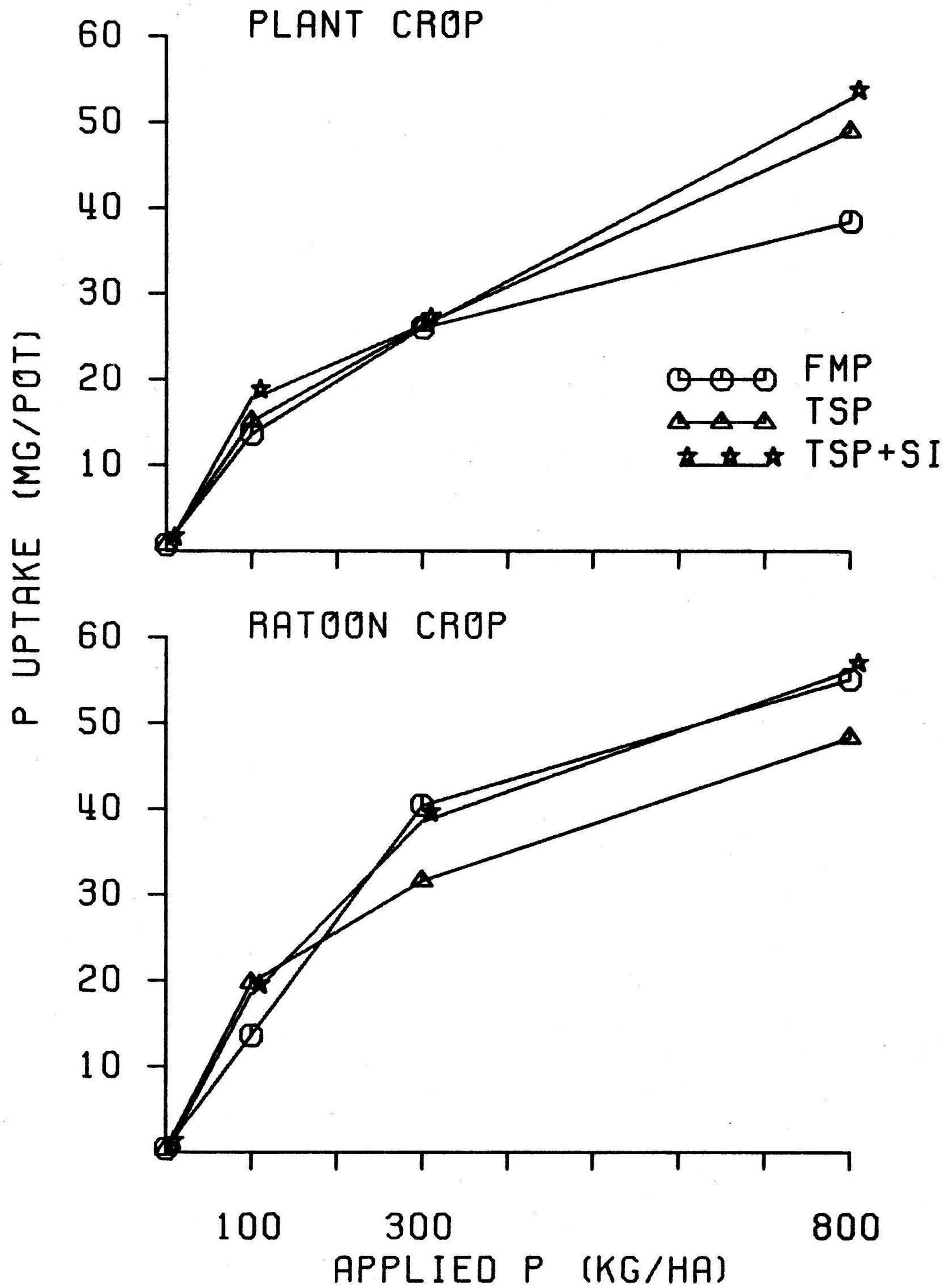
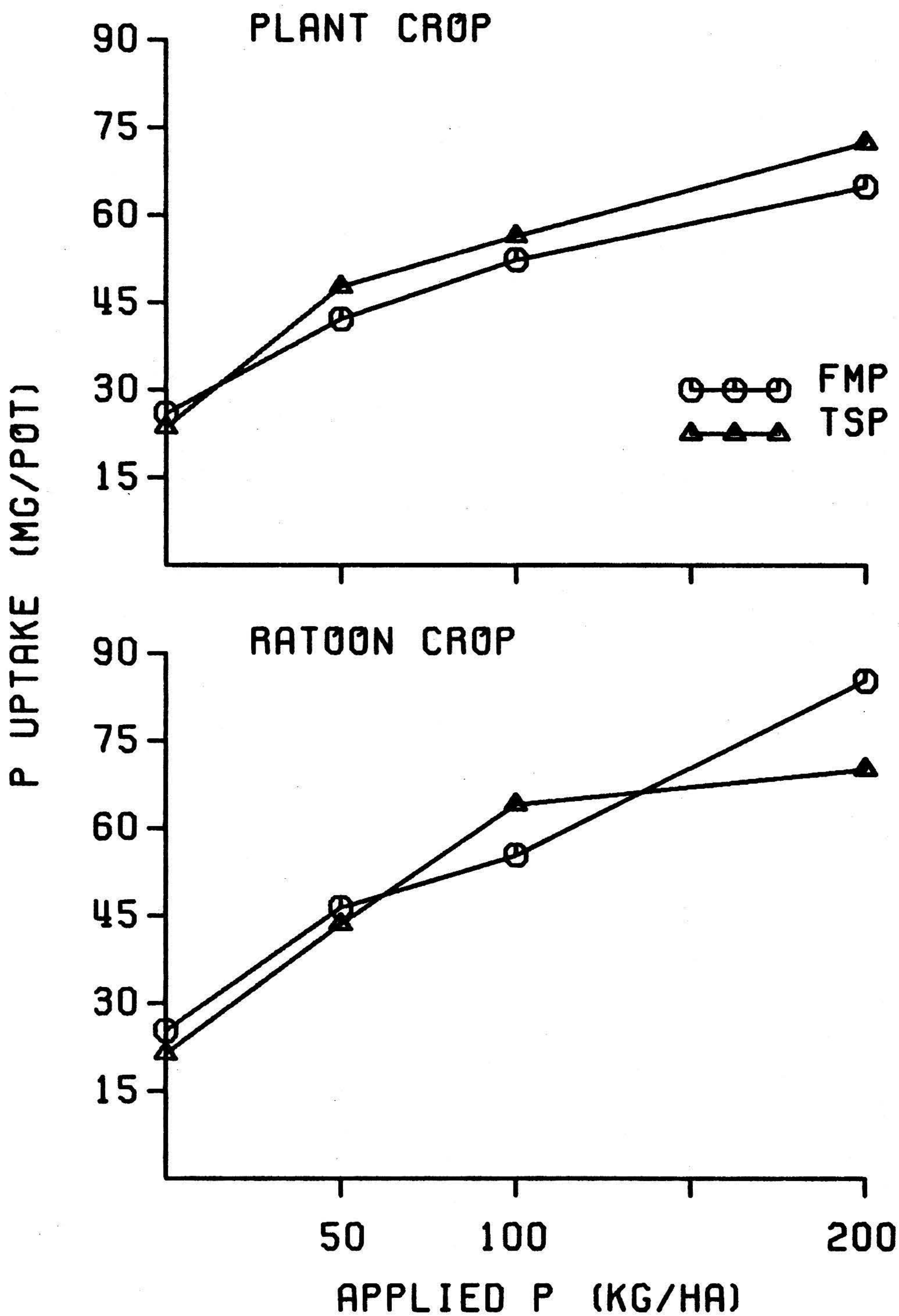

PLANT CROP
RATOON CROP
FMP
TSP
TSP+SI
P UPTAKE (MG/POT)
APPLIED P (KG/HA)
60
50
40
30
20
10
100
300
800

Figure 7. Variation in P uptake by Sudax with rate and source of P applied to the Lualualei soil


PLANT CROP
RATOON CROP
FMP
TSP
P UPTAKE (MG/POT)
APPLIED P (KG/HA)
90
75
60
45
30
15
50
100
200

The three granule sizes of FMP applied to the Halii soil had the same effect on P concentration in the plant crop. However, in the ratoon crop the coarse fraction (CF) gave higher plant P than the normal size (NS) and the fine fraction (FF) (compare 0.13% vs. 0.12 and 0.11%) (Figure 8, Appendix Table 8). The same pattern occured in the uptake of P (Figure 9, Appendix Table 9). This again was attributed to the slightly higher total P content in the CF and its being less subject to fixation by the soil than the other two sizes.

Plant Mg. The different forms of fertilizer P had different effects on plant Mg. Fused magnesium phosphate (NS) applied to the Halii soil resulted in significant increases in plant Mg with increasing amounts of applied P in both harvests (Figure 10). Magnesium concentrations in the plant crop increased from 0.30%, when no FMP was added, to 0.83% when 800 Kg P/ha was added as FMP(NS). In the ratoon crop it increased from 0.30% to 0.87% (Appendix Table 10). The average plant Mg concentrations given by FMP(NS) in the plant and ratoon crops were 0.53 and 0.58%, respectively. These were significantly higher than Mg concentrations given by TSP applications with and without Si. This was explained by the fact that FMP(NS) contains 9% Mg. Treble superphosphate and treble superphosphate with silicate caused similar levels of plant Mg and followed essentially the same pattern. In the plant crop of the Halii soil there may have been a dilution effect on the concentration of plant magnesium

Figure 8. Variation in plant P in Sudax with rate and granule size of FMP applied to the Halii soil

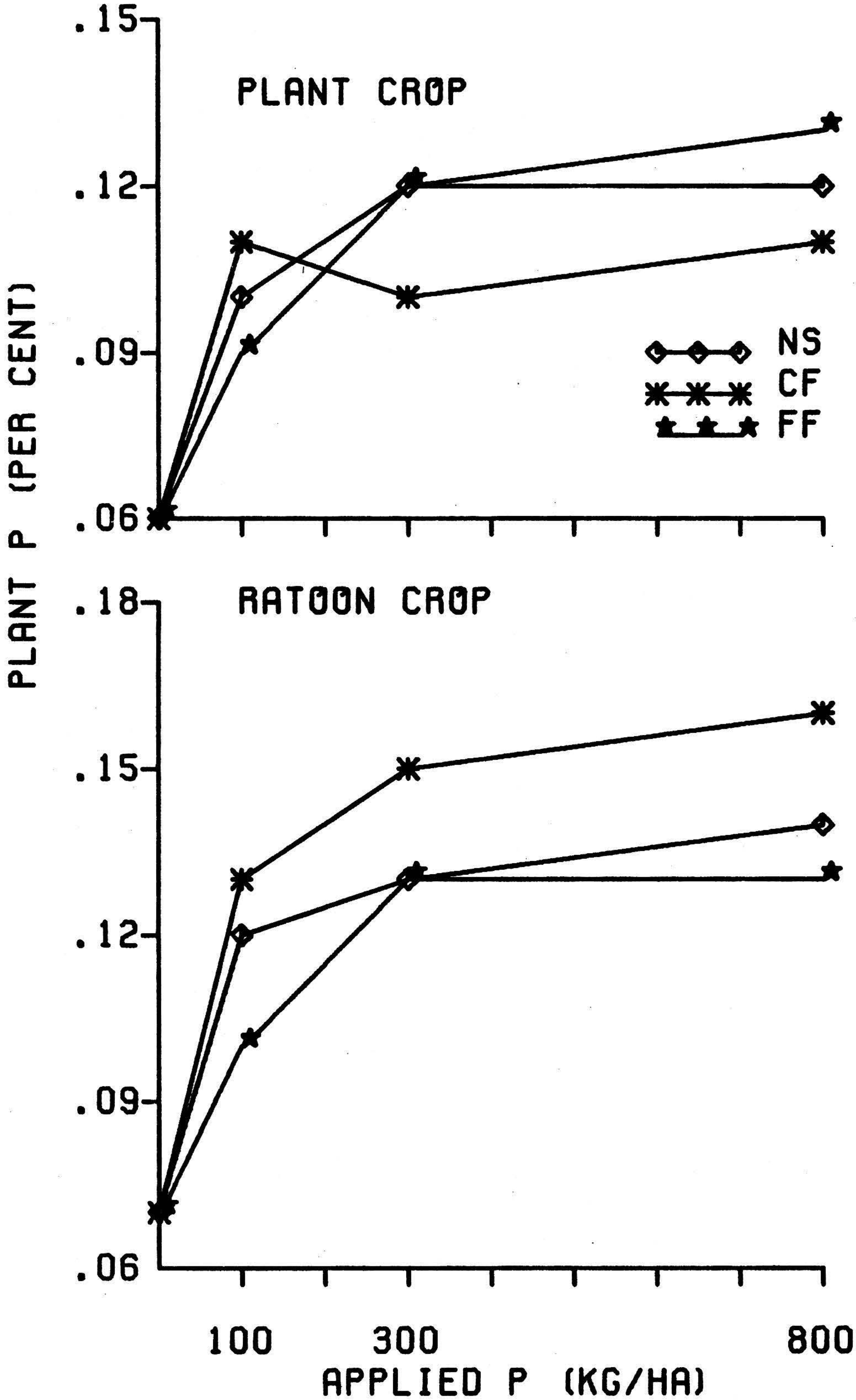

PLANT CROP
RATOON CROP
NS
CF
FF
PLANT P (PER CENT)
.15
.12
.09
.06
.18
.15
.12
.09
.06
100
300
800
APPLIED P (KG/HA)

Figure 9. Variation in P uptake by Sudax with rate and granule size of FMP applied to the Halii soil

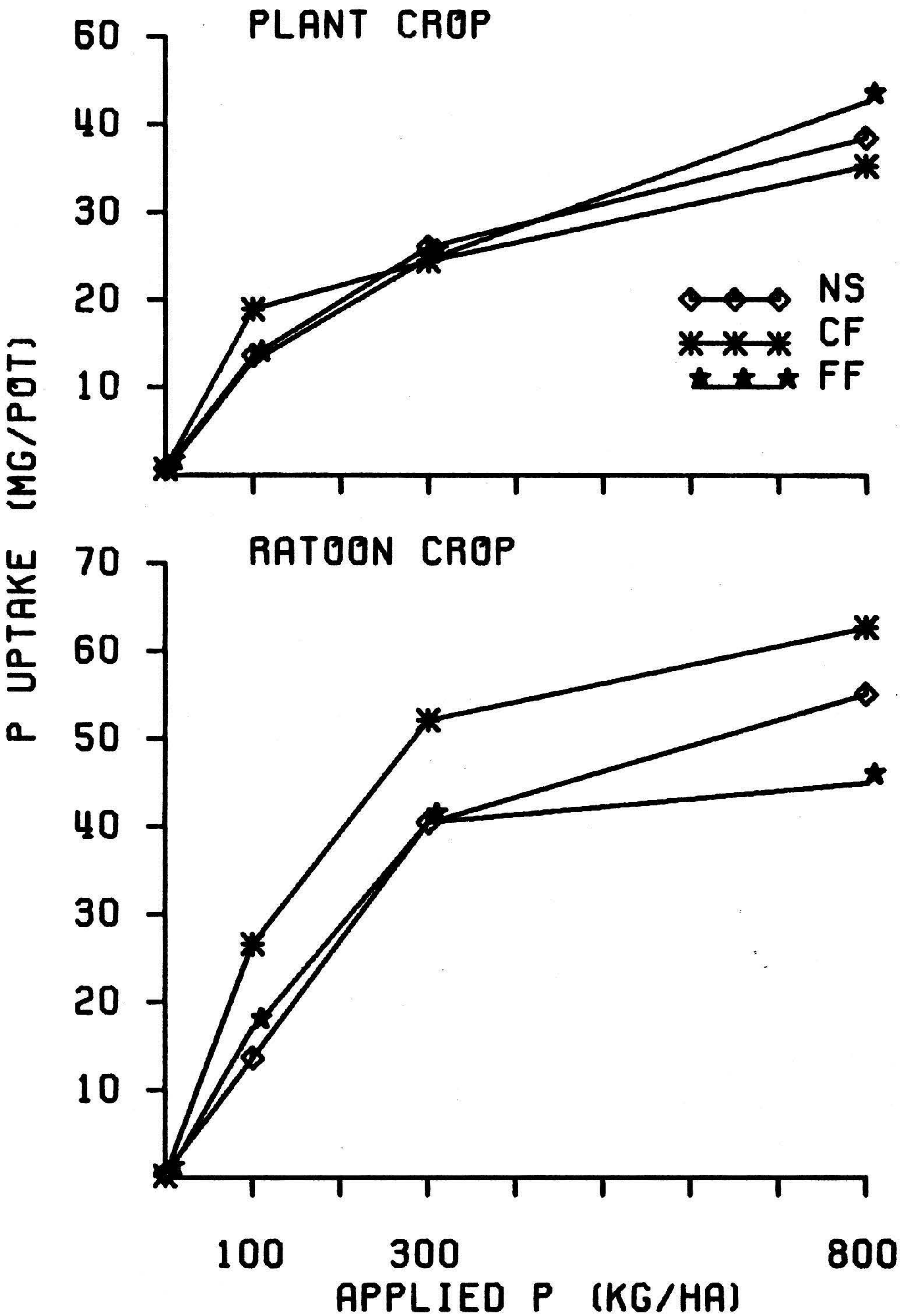
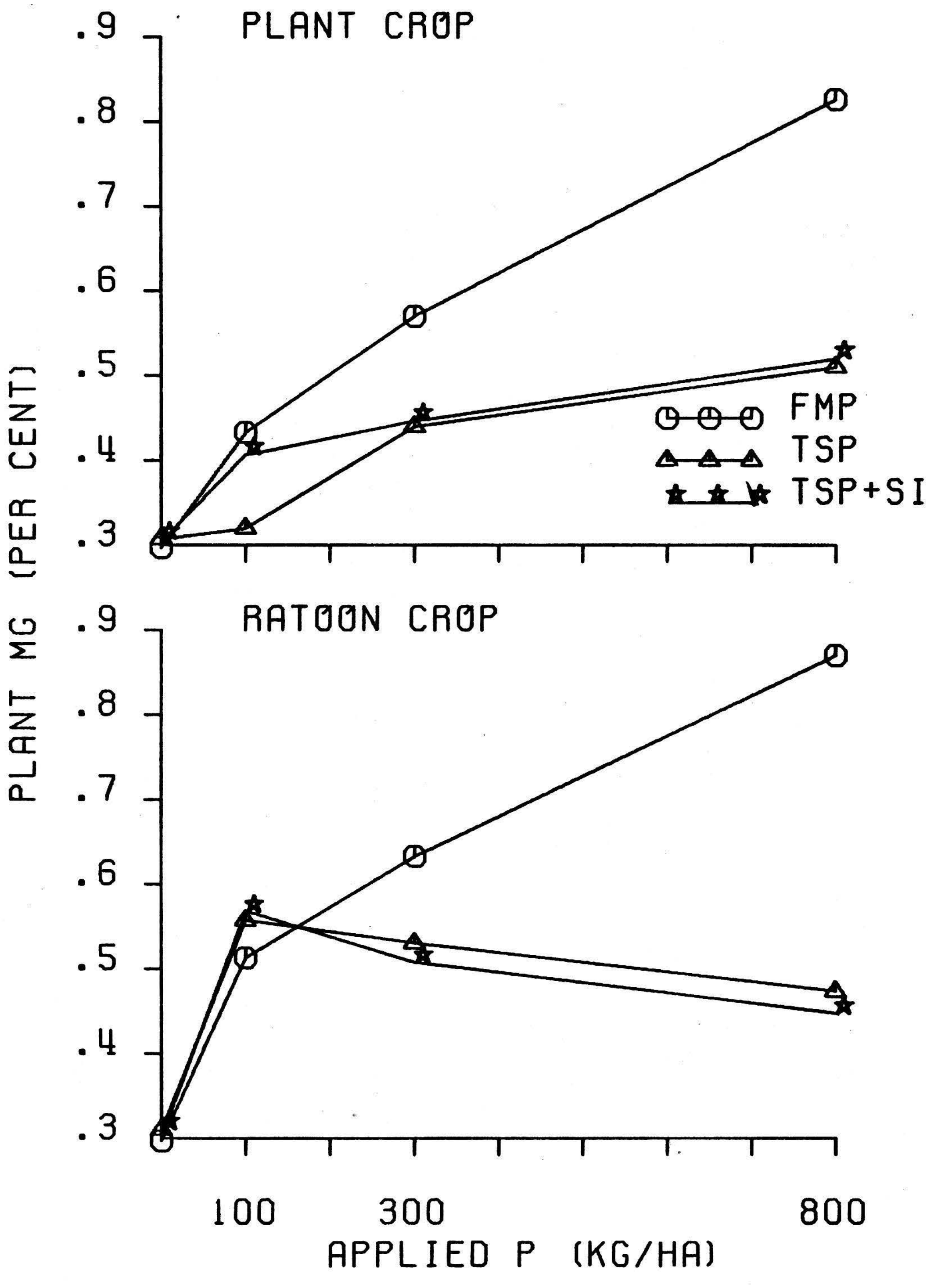

PLANT CROP
60
40
30
20
10
NS
CF
FF
P UPTAKE (MG/POT)
RATOON CROP
70
60
50
40
30
20
10
100
300
800
APPLIED P (KG/HA)

Figure 10. Variation in plant Mg in Sudax with rate and source of P applied to the Halii soil


PLANT CROP
RATOON CROP
PLANT MG (PER CENT)
.9
.8
.7
.6
.5
.4
.3
FMP
TSP
TSP+SI
100
300
800
APPLIED P (KG/HA)

which reduced the level of plant Mg with TSP and TSP with Si. Also in the ratoon crop a yield-induced dilution effect as well as reduced levels of soil Mg may have been responsible for lower Mg concentrations with increasing amounts of TSP and TSP with Si as reported by Khalid (1974).

In the Lualualei soil plant Mg levels were similar with FMP(NS) and TSP in both harvests (Figure 11, Appendix Table 11). This was attributed to the high level of native Mg in Lualualei soil (Table 2).

The relationship between Mg uptake and rate and form of applied P is illustrated in Figures 12 and 13 for Halii and Lualualei soils, respectively. In the Halii soil Mg uptake was significantly higher with FMP(NS) application in plant and ratoon crops than with TSP and TSP + Si applications. This was attributed to the higher plant Mg concentrations with FMP(NS) applications. In the Lualualei soil Mg uptake was significantly higher with TSP than FMP in the plant crop (Appendix Table 13). This was explained by the higher dry matter yield with TSP. In the ratoon crop Mg uptake was similar with both FMP(NS) and TSP because dry matter yields were similar.

The three sizes of FMP applied to the Halii soil behaved similarly in supplying Mg to the plant as well as the ratoon crop (Figures 14 and 15, Appendix Tables 14 and 15).

Figure 11. Variation in plant Mg in Sudax with rate and source of P applied to the Lualualei soil

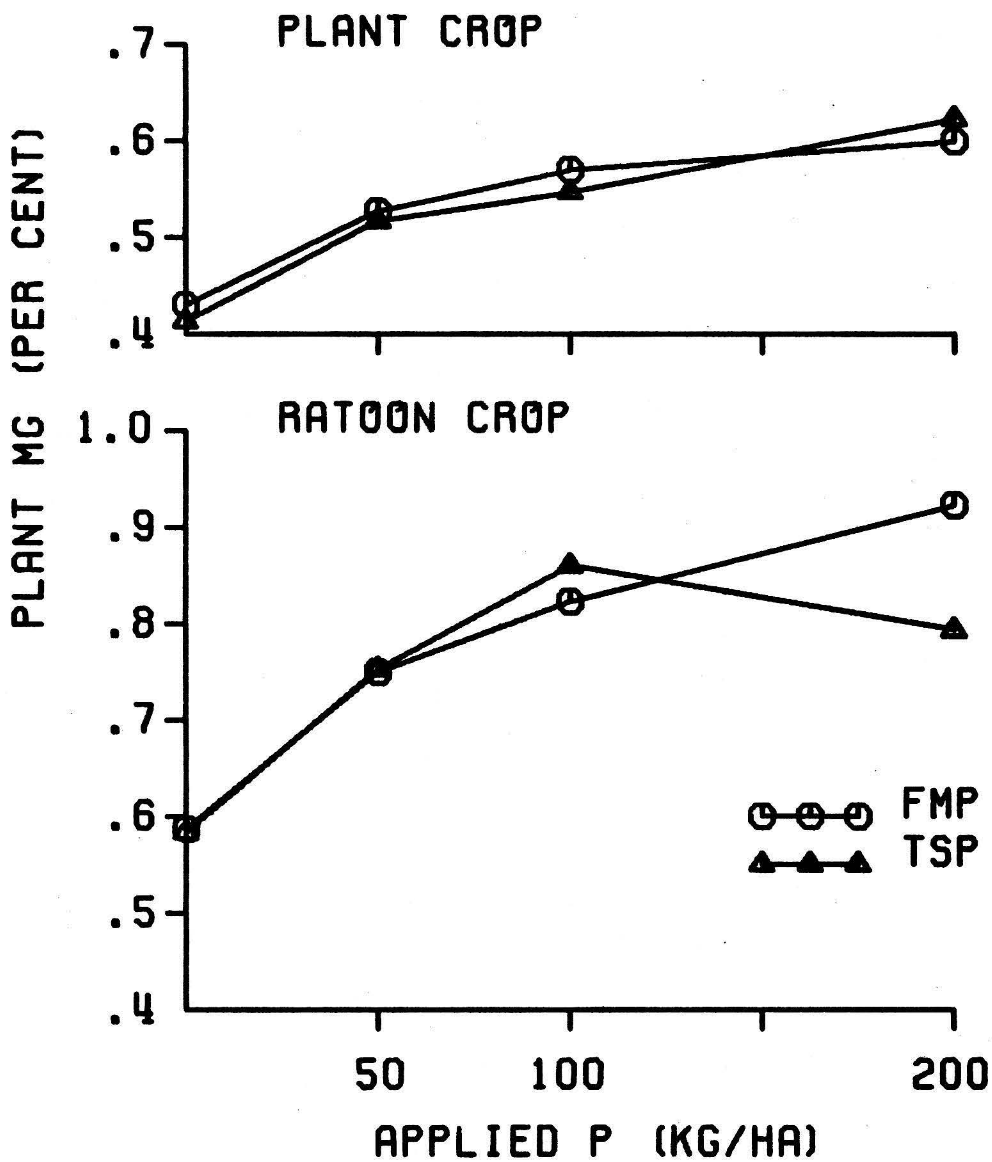

PLANT CROP
RATOON CROP
PLANT MG (PER CENT)
.7
.6
.5
.4
1.0
.9
.8
.7
.6
.5
.4
50
100
200
APPLIED P (KG/HA)
FMP
TSP

Figure 12. Variation in Mg uptake by Sudax with rate and source of P applied to the Halii soil

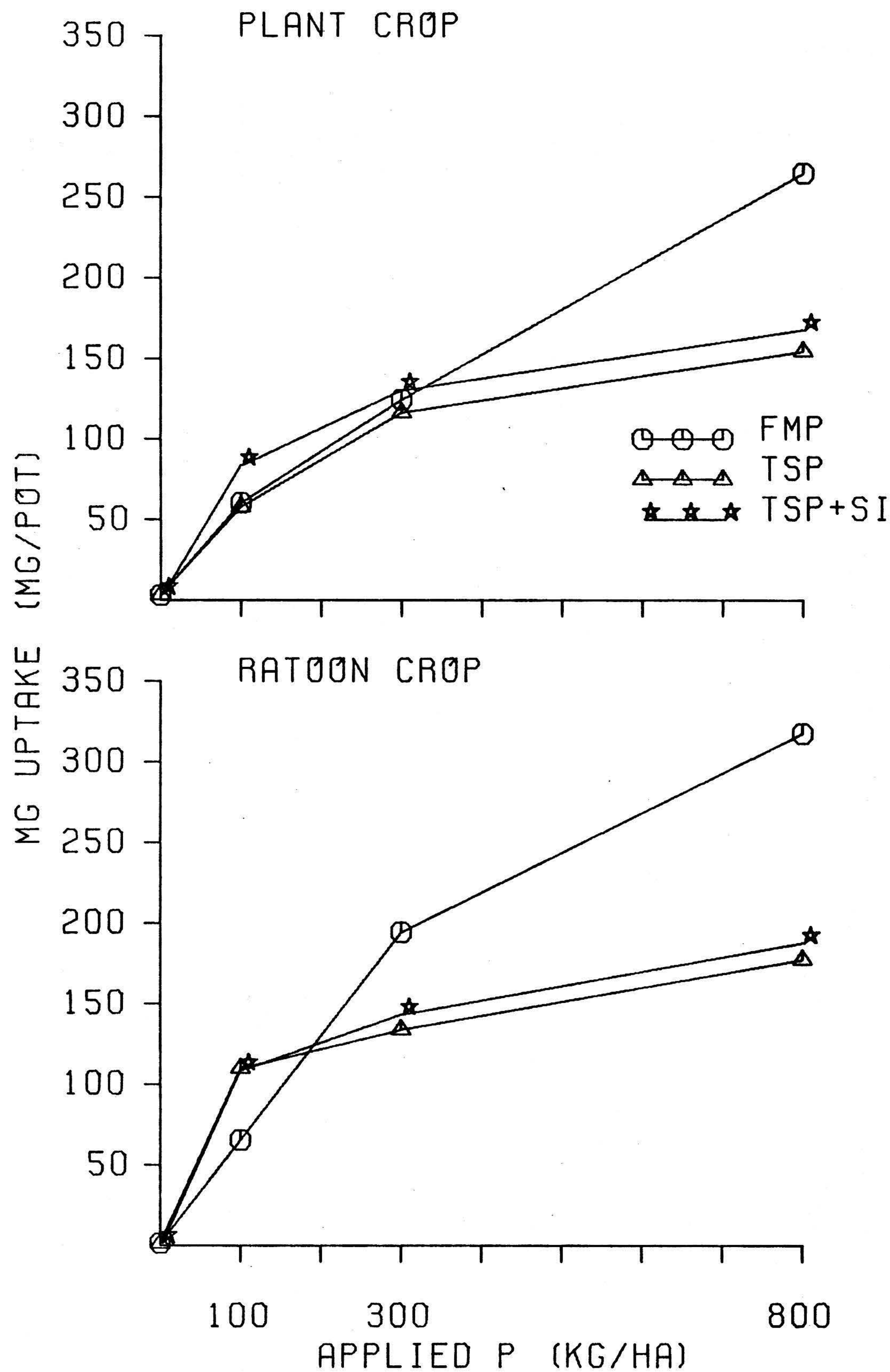

PLANT CROP
RATOON CROP
FMP
TSP
TSP+SI
MG UPTAKE (MG/POT)
APPLIED P (KG/HA)
350
300
250
200
150
100
50
100
300
800

Figure 13. Variation in Mg uptake by Sudax with rate and source of P applied to the Lualualei soil

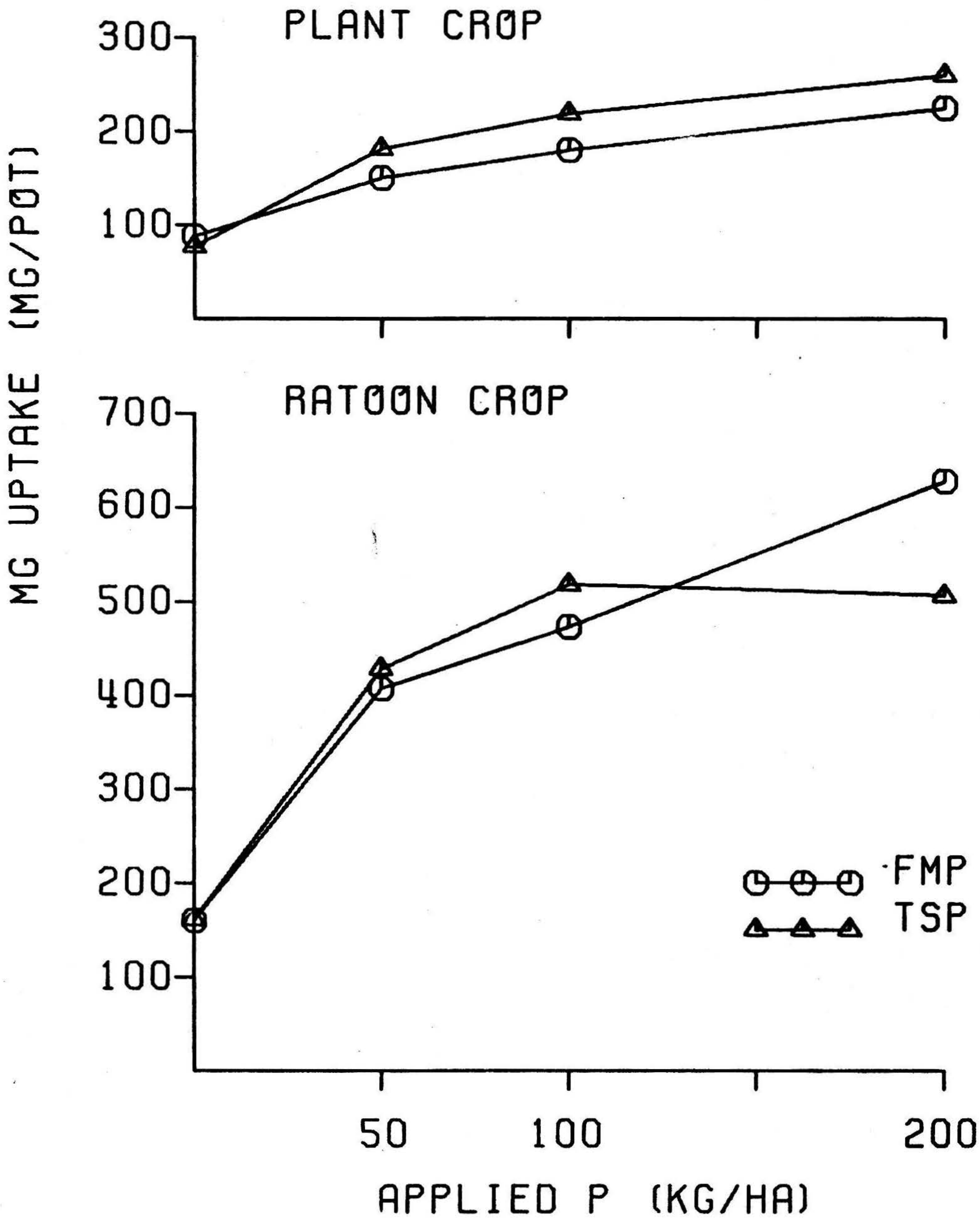

PLANT CROP
300
200
100
RATOON CROP
700
600
500
400
300
200
100
MG UPTAKE (MG/POT)
FMP
TSP
50
100
200
APPLIED P (KG/HA)

Figure 14. Variation in plant Mg in Sudax with rate and granule size of FMP applied to the Halii soil

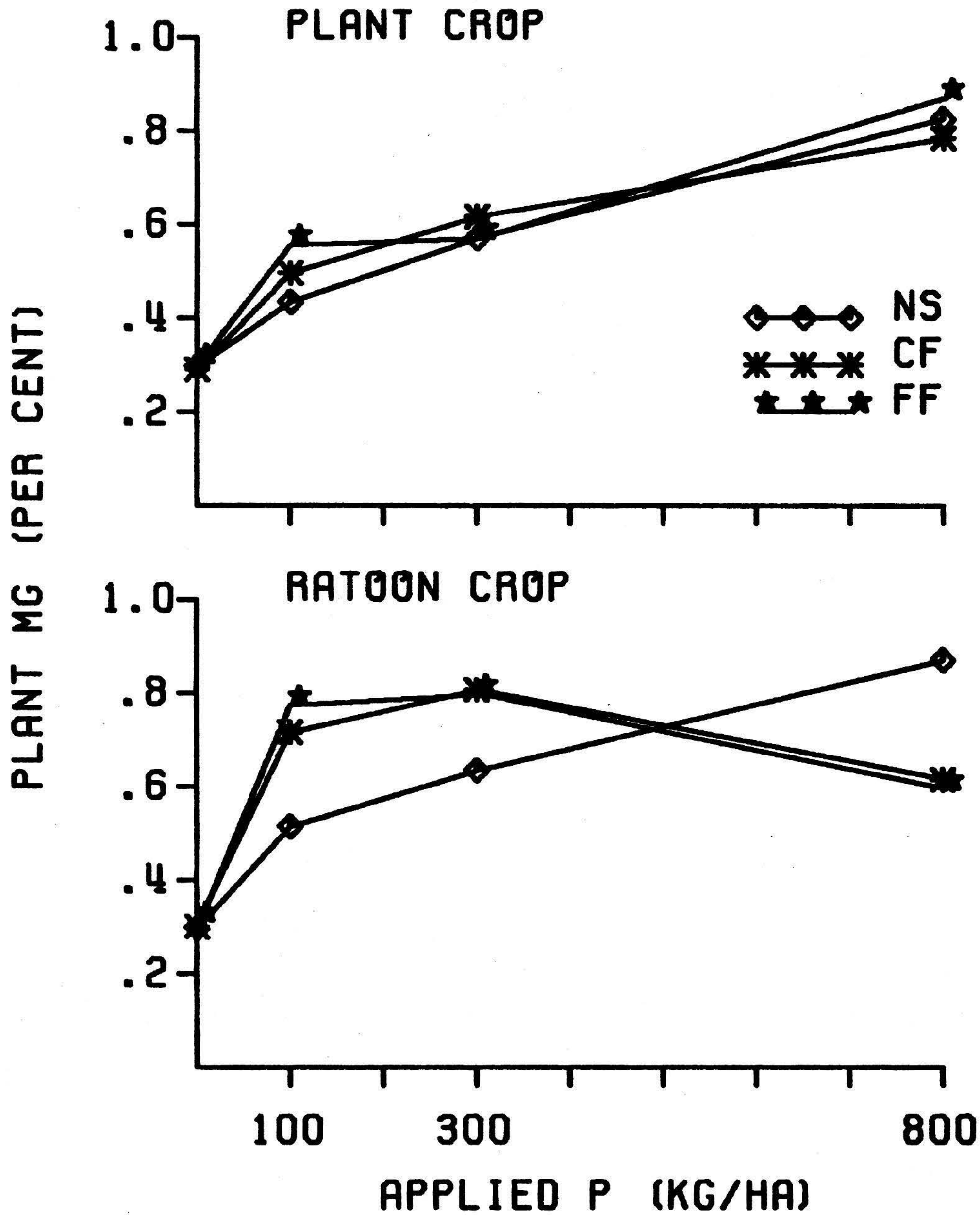
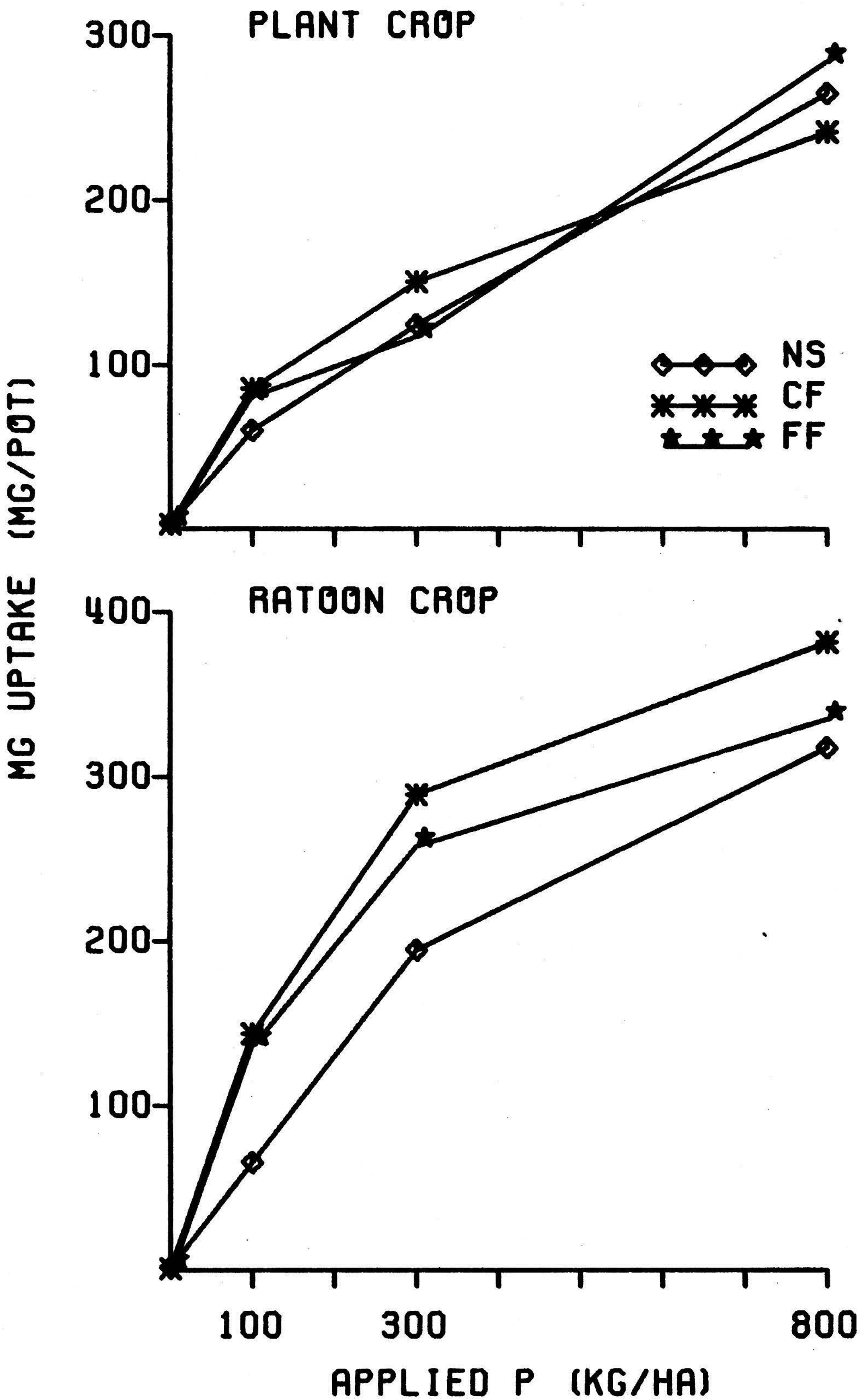
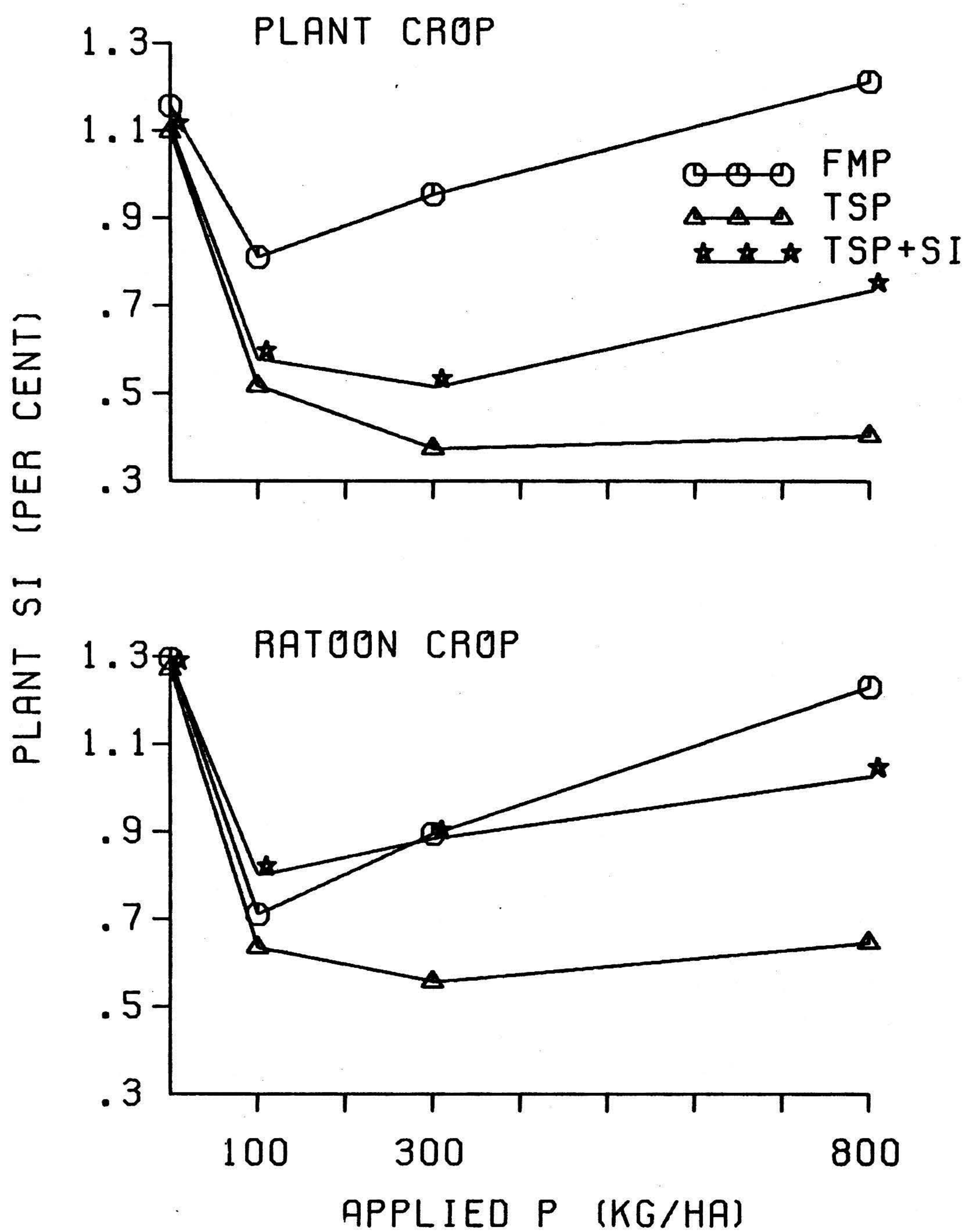

PLANT CROP
RATOON CROP
1.0
.8
.6
.4
.2
NS
CF
FF
PLANT MG (PER CENT)
100
300
800
APPLIED P (KG/HA)

Figure 15. Variation in Mg uptake by Sudax with rate and granule size of FMP applied to the Halii soil


PLANT CROP
300
200
100
NS
CF
FF
MG UPTAKE (MG/POT)
RATOON CROP
400
300
200
100
100
300
800
APPLIED P (KG/HA)

Plant Si. Silicon concentration in the plant decreased significiantly in both plant and ratoon crops with the application of 100 kgP/ha as FMP(NS), TSP or TSP + Si to the Halii soil (Figure 16). This may be due to a dilution effect from the increased yield. Further applications of FMP(NS) resulted in increased plant Si concentration. However, further applications of TSP, with or without Si, had little or no effect on plant Si. This suggested that FMP(NS) at higher rates may have a stimulating effect on Si absorption. Absorption of Si by plant roots is controlled not only by soil Si levels and characteristics of plant species (Khalid, 1974) but also by the amount of Si applied. In the plant crop of the Halii soil plant Si concentrations differed significantly with the three forms of applied P (Appendix Table 16). Plant Si concentrations were highest with FMP(NS) followed by TSP + Si and then TSP. However, in the ratoon crop FMP(NS) and TSP with Si apparently supplied comparable amounts of Si (compare 1.03% vs. 1.00%) while TSP alone supplied little, if any Si (0.78%). These results suggest that Si in FMP(NS) is more soluble and hence more available to plants than that in $CaSiO_3$. Also Si in $CaSiO_3$ became more soluble with time. The higher levels of plant Si with applications of FMP(NS) suggested that this material may have provided more resistance against insects and wind if the plants were grown in the field rather than in a controlled environment.

Figure 16. Variation in plant Si in Sudax with rate and source of P applied to the Halii soil


PLANT CROP
RATOON CROP
FMP
TSP
TSP+SI
1.3
1.1
.9
.7
.5
.3
PLANT SI (PER CENT)
100
300
800
APPLIED P (KG/HA)

In the Lualualei soil Si concentrations in the plant crop decreased with the first rate of applied FMP(NS) and TSP (50 kgP/ha) as in the Halii soil (Figure 17). This was again attributed to a dilution effect caused by increased dry matter yield. Further applications of FMP(NS) and TSP increased plant Si concentrations, but not significantly (Appendix Table 17). Applied P may have increased the availability of Si and improved root development resulting in increased absorption of Si. This was better demonstrated in the ratoon crop in which Si concentrations in the plant increased significantly with all rates of applied FMP(NS) and TSP. Plant Si concentrations were higher with FMP(NS) than TSP in both harvests, but the difference was not significant. This indicates that the Si level in the Lualualei soil is sufficiently high so that application of Si did not increase the Si level.

Silicon taken up by the plant and ratoon crops increased with increased amounts of applied FMP(NS), TSP and TSP with Si (Figures 18 and 19). This was mainly attributed to increased dry matter yield with fertilizer P applications. Fused magnesium phosphate (NS) resulted in the highest amount of average Si uptake by the plant crop in the Halii soil followed by TSP + Si and then TSP (compare 180.1 mg/pot vs 129.5 and 82.2 mg/pot). In the ratoon crop Si uptake was similar with FMP(NS) and TSP + Si and was significantly higher than Si uptake with TSP

Figure 17. Variation in plant Si in Sudax with rate and source of P applied to the Lualualei soil

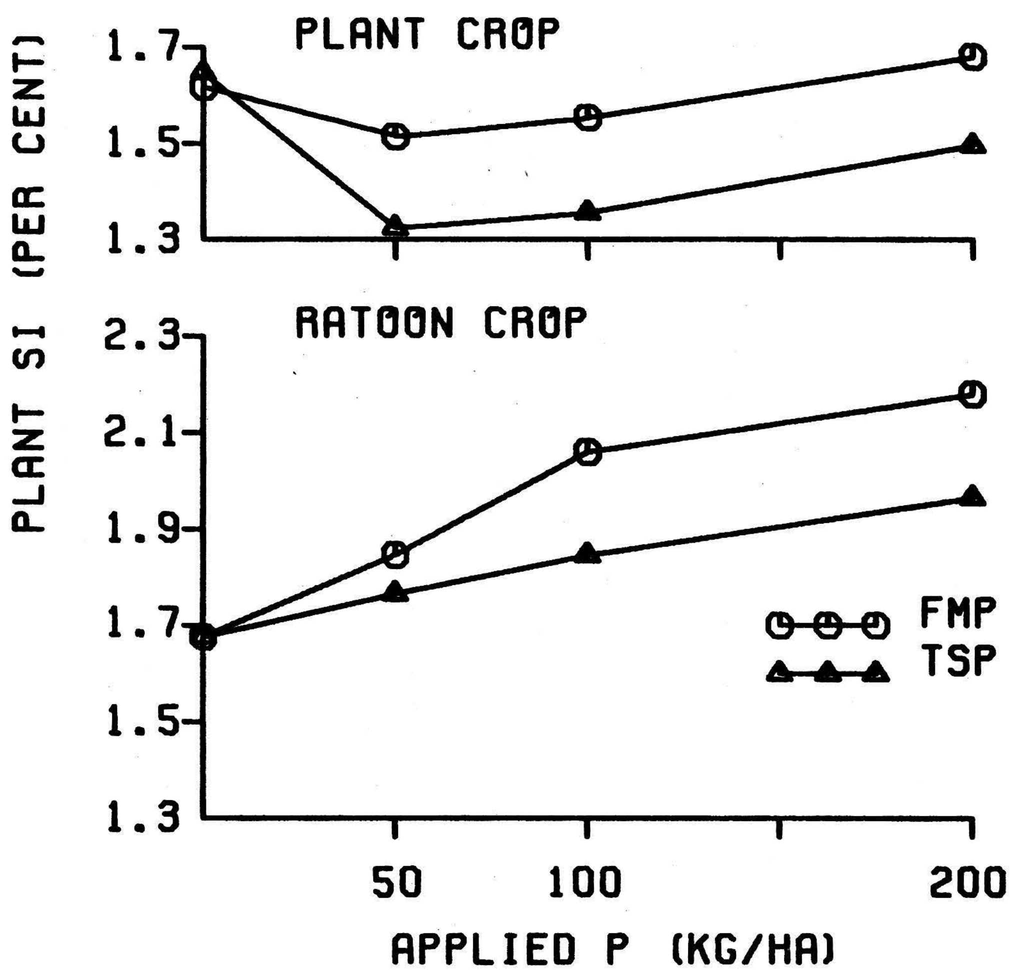

PLANT CROP
RATOON CROP
PLANT SI (PER CENT)
1.7
1.5
1.3
2.3
2.1
1.9
1.7
1.5
1.3
50
100
200
APPLIED P (KG/HA)
FMP
TSP

Figure 18. Variation in Si uptake by Sudax with rate and source of P applied to the Halii soil

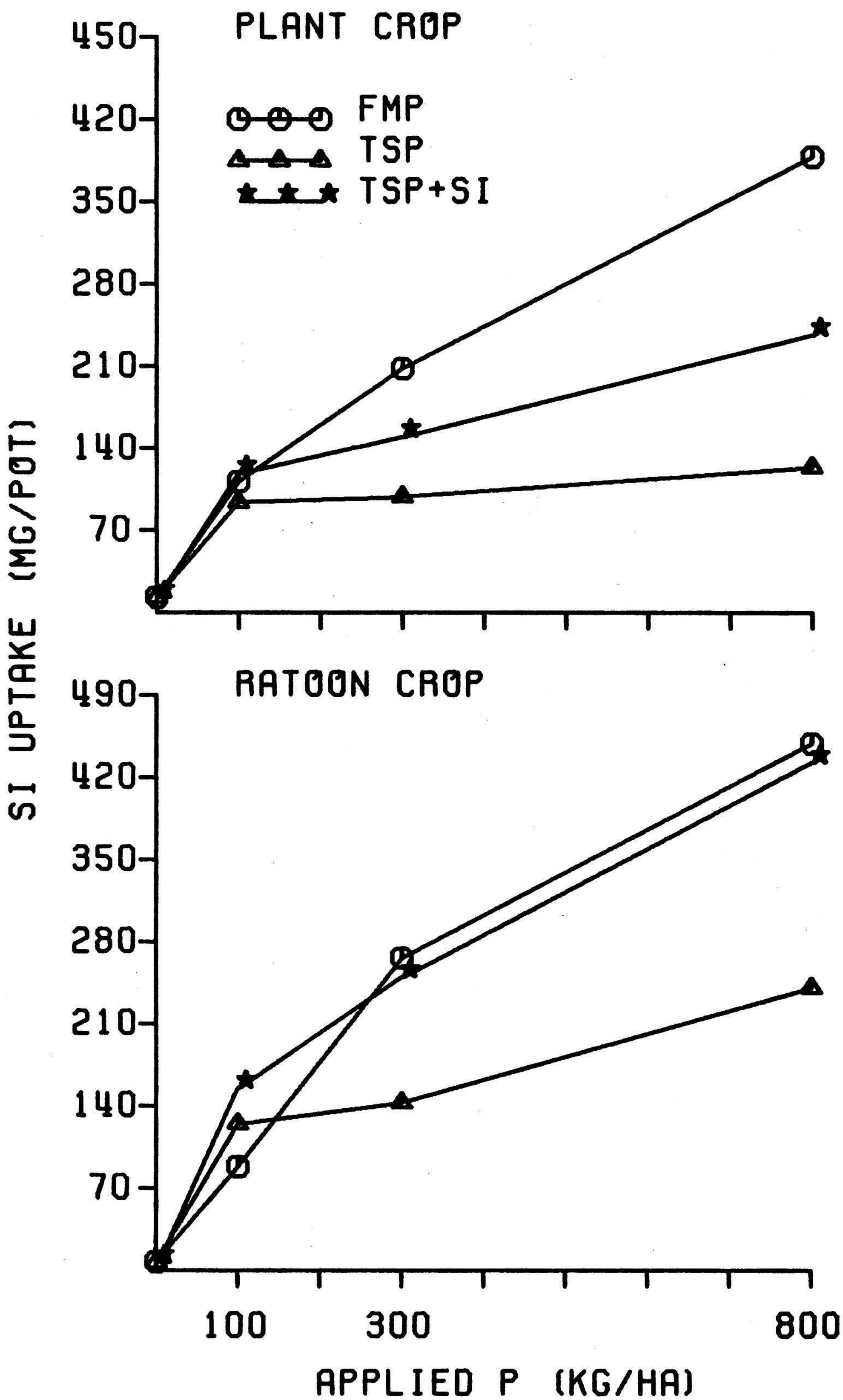
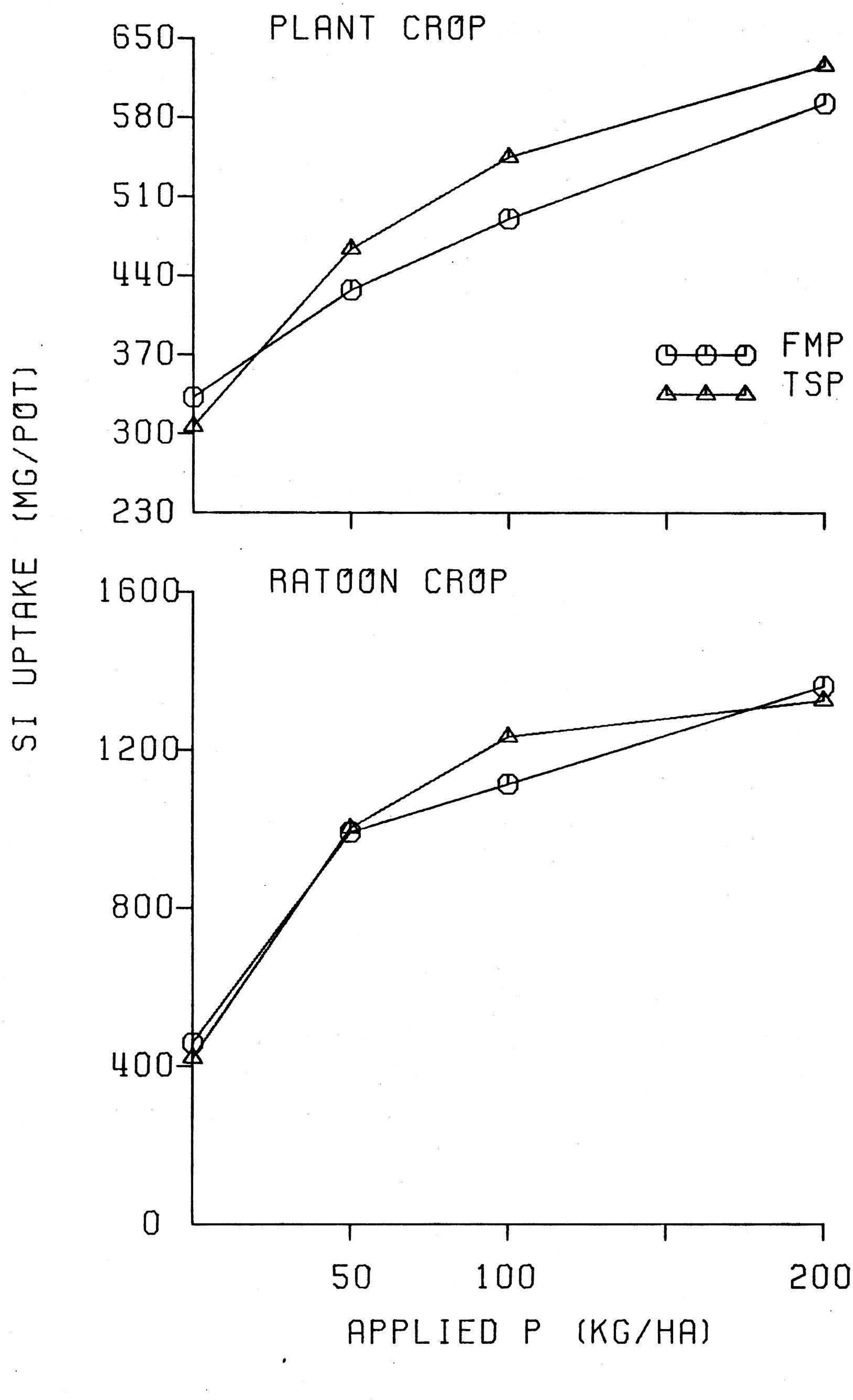

PLANT CROP
FMP
TSP
TSP+SI
450
420
350
280
210
140
70
SI UPTAKE (MG/POT)
RATOON CROP
490
420
350
280
210
140
70
100
300
800
APPLIED P (KG/HA)

Figure 19. Variation in Si uptake by Sudax with rate and source of P applied to the Lualualei soil


PLANT CROP
RATOON CROP
SI UPTAKE (MG/POT)
APPLIED P (KG/HA)
FMP
TSP
650
580
510
440
370
300
230
1600
1200
800
400
0
50
100
200

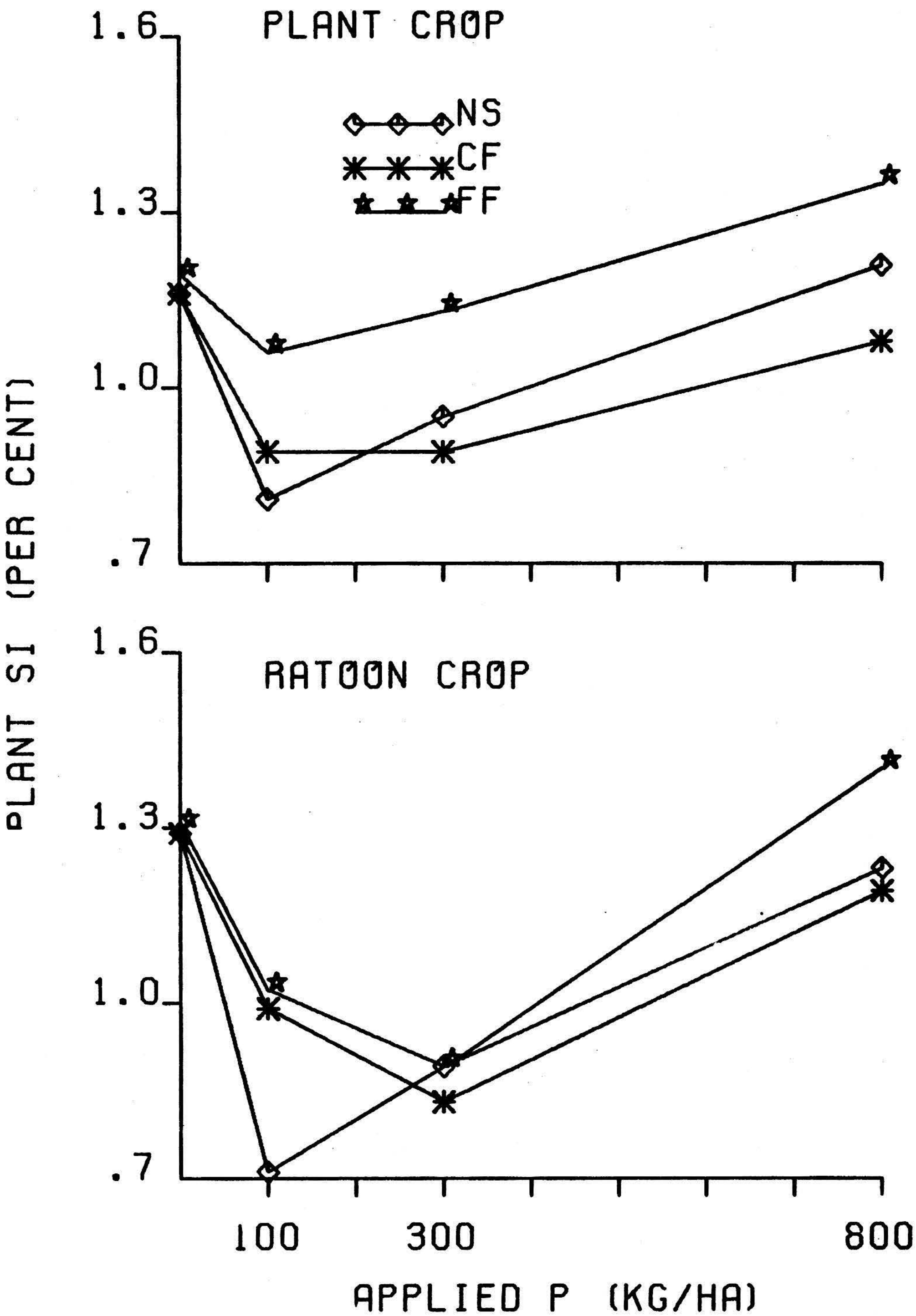
alone (compare 202.5 and 210.9 mg/pot vs. 128.8 mg/pot) (Appendix Table 18). In the Lualualei soil Si uptake with FMP(NS) and TSP was similar in both harvests (Figure 19, Appendix table 19).

The normal size (NS) and coarse fraction (CF) of FMP applied to the Halii soil apparently supplied comparable amounts of Si to the plant crop of Sudax while the fine fraction (FF) supplied a significantly higher amount (compare 1.03 and 1.01% vs. 1.18%) (Figure 20, Appendix Table 20). This suggests that the fine fraction is more soluble than the other fractions and hence more available to plants. In the ratoon crop the fine fraction continued to supply more Si to the plants than the other two fractions, but the difference was not significant. The three granule sizes of FMP resulted in comparable amounts of Si uptake in both plant and ratoon crops (Figure 21, Appendix Table 21).

Plant Ca. Calcium concentrations in the plant crop grown on the Halii soil increased significantly with increasing amounts of FMP(NS), TSP and TSP + Si (Figure 22). This was attributed to Ca from FMP, TSP and TSP + Si. In the ratoon crop plant Ca concentration decreased at the highest P rate because of a dilution effect.

Although FMP contained almost four times as much Ca as TSP (Table 3), both P sources resulted in similar plant Ca concentrations in both plant and ratoon crops in the two soils (Figures 22 and 23, Appendix Tables 22 and 23).

Figure 20. Variation in plant Si in Sudax with rate and granule size of FMP applied to the Halii soil



PLANT CROP
NS
CF
FF
RATOON CROP
1.6
1.3
1.0
.7
PLANT SI (PER CENT)
100
300
800
APPLIED P (KG/HA)

Figure 21. Variation in Si uptake by Sudax with rate and granule size of FMP applied to the Halii soil

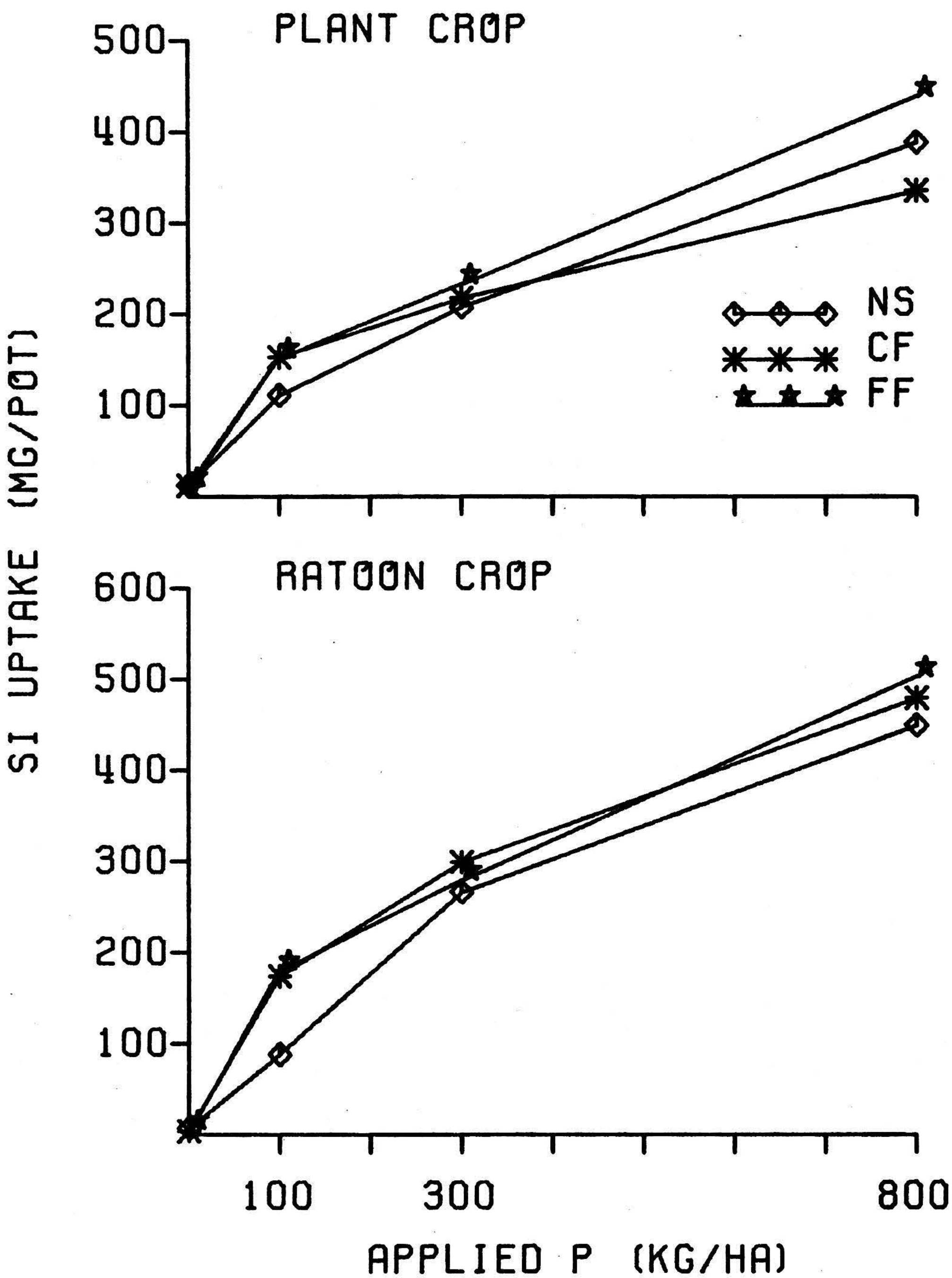
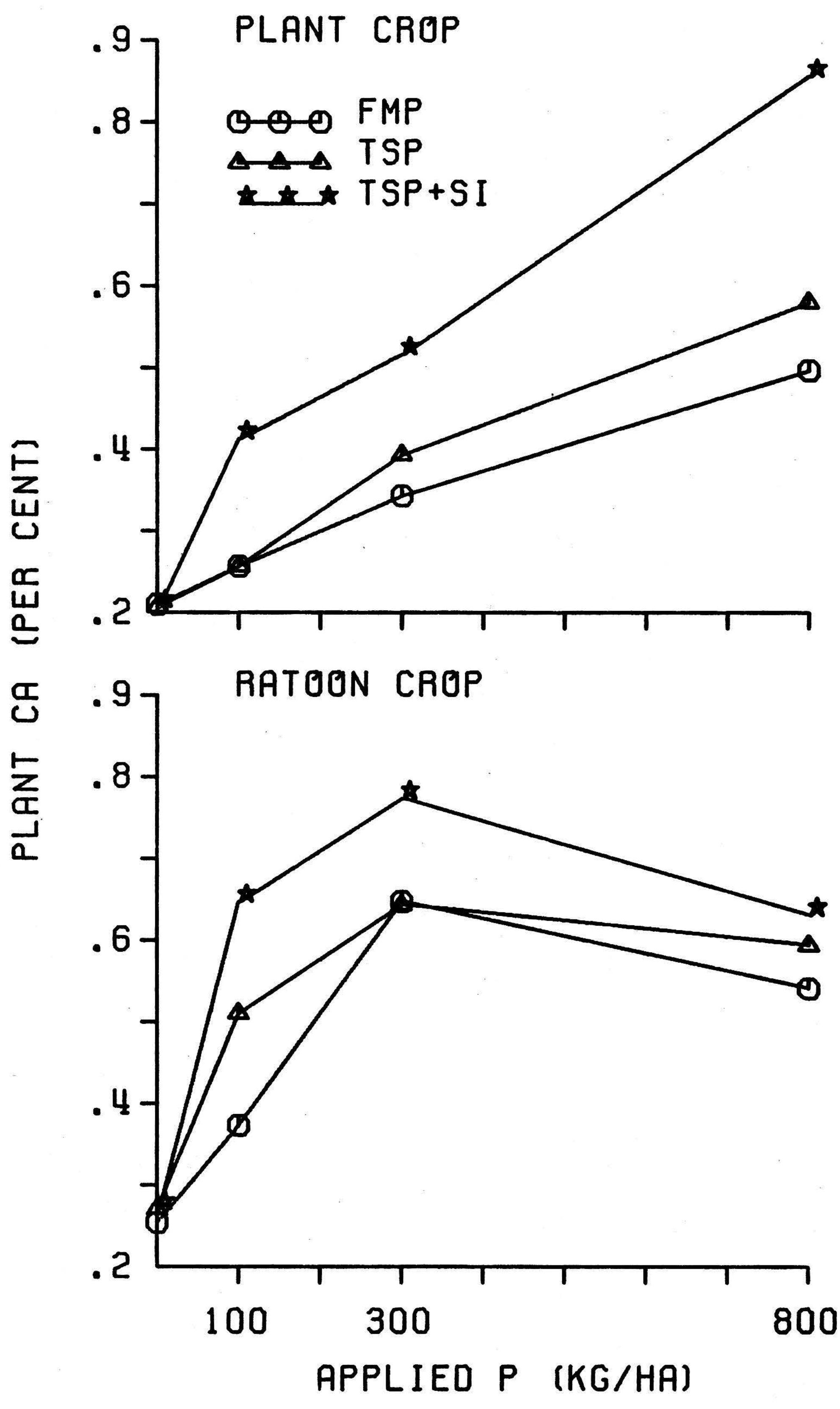
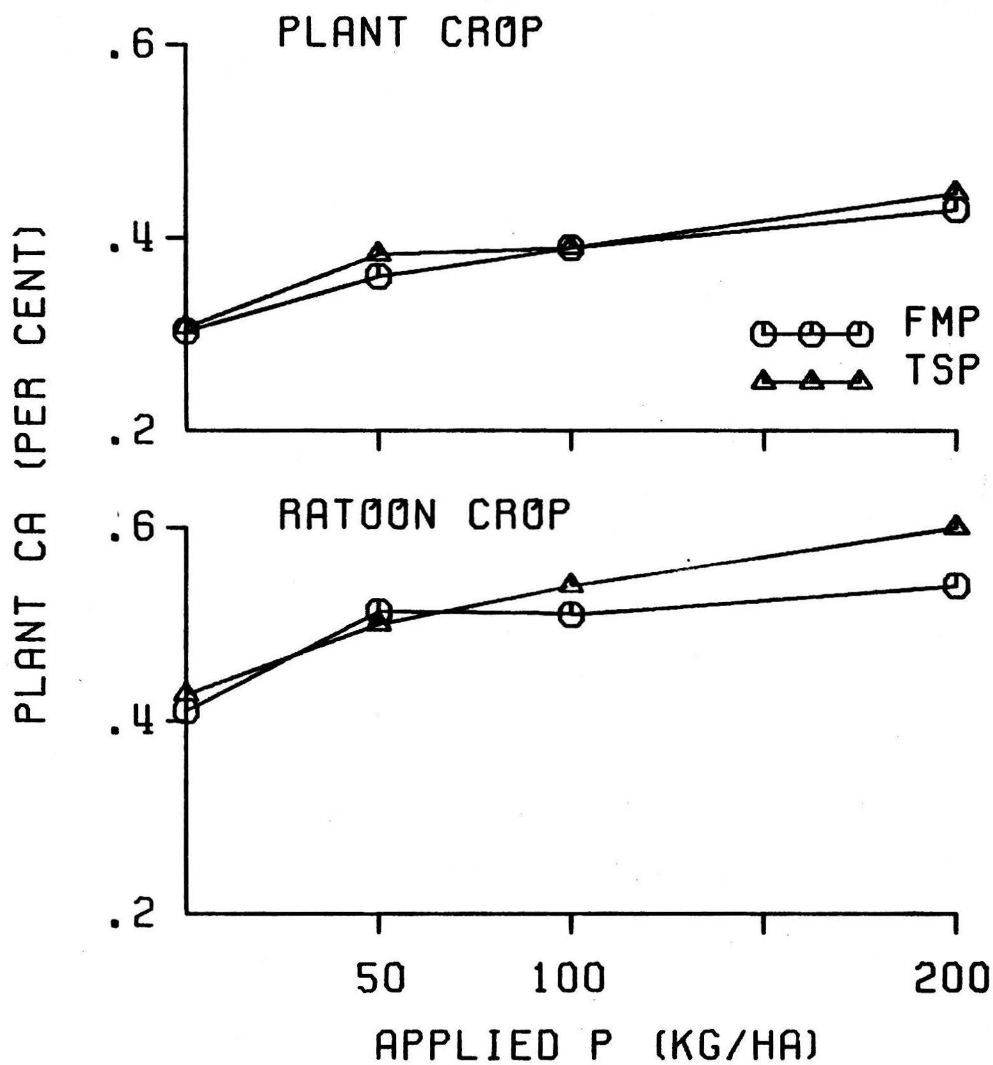

PLANT CROP
500
400
300
200
100
NS
CF
FF
RATOON CROP
600
500
400
300
200
100
SI UPTAKE (MG/POT)
100
300
800
APPLIED P (KG/HA)

Figure 22. Variation in plant Ca in Sudax with rate and source of P applied to the Halii soil



PLANT CROP
FMP
TSP
TSP+SI
RATOON CROP
PLANT CA (PER CENT)
.9
.8
.6
.4
.2
100
300
800
APPLIED P (KG/HA)

Figure 23. Variation in plant Ca in Sudax with rate and source of P applied to the Lualualei soil

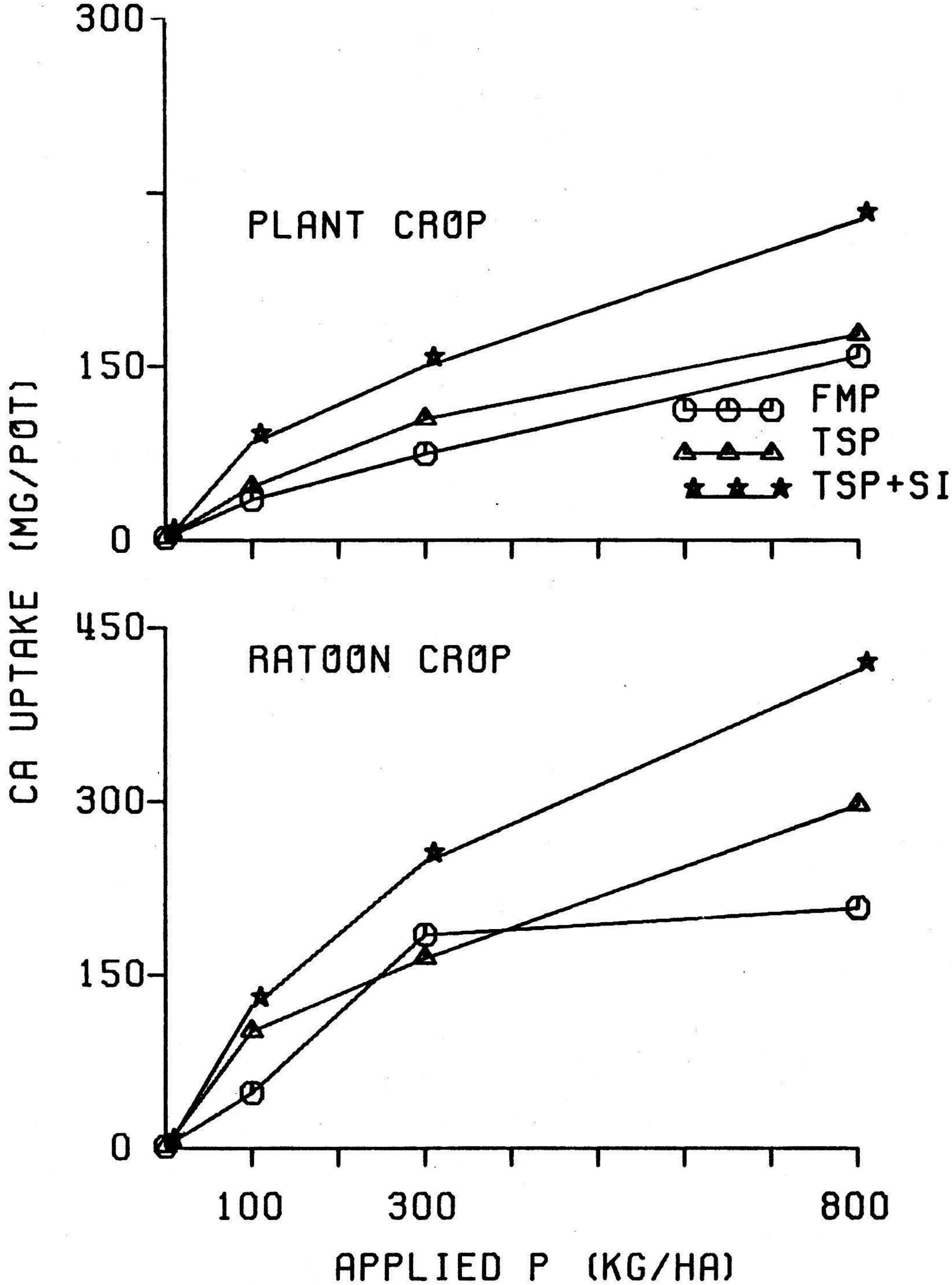

PLANT CROP
RATOON CROP
PLANT CA (PER CENT)
.6
.4
.2
FMP
TSP
50
100
200
APPLIED P (KG/HA)

This may be due to the low solubility of FMP in water. Treble superphosphate applied together with $CaSiO_3$ to the Halii soil resulted in significantly higher plant Ca concentrations than FMP(NS) and TSP in the plant crop. This was caused by the Ca added with $CaSiO_3$. In the ratoon crop there was no significant difference in average plant Ca between the three materials at the 5% level of probability.

Calcium uptake in both soils followed the same pattern as the dry matter yield. In the Halii soil TSP applied together with $CaSiO_3$ resulted in the highest Ca uptake followed by TSP and then FMP(NS) in both harvests (Figure 24, Appendix Table 24). In the Lualualei soil Ca uptake with TSP was greater than with FMP(NS) in the plant crop (Figure 25). However, in the ratoon crop the two P sources were equally effective.

Plant Ca concentrations were comparable with the three granule sizes of FMP applied to the Halii soil in the plant as well as the ratoon crop (Appendix Table 26). Figure 26 illustrates that the three sizes supply similar amounts of Ca to Sudax. Plant Ca concentrations were higher in the ratoon crop than in the plant crop. This indicated that the three granule sizes of FMP became more soluble with time. The three granule sizes of FMP applied to the Halii soil resulted in comparable amounts of Ca uptake by Sudax (Figure 27, Appendix Table 27).

Figure 24. Variation in Ca uptake by Sudax with rate and source of P applied to the Halii soil



300
150
0
PLANT CROP
FMP
TSP
TSP+SI
450
300
150
0
RATOON CROP
CA UPTAKE (MG/POT)
100
300
800
APPLIED P (KG/HA)

Figure 25. Variation in Ca uptake by Sudax with rate and source of P applied to the Lualualei soil

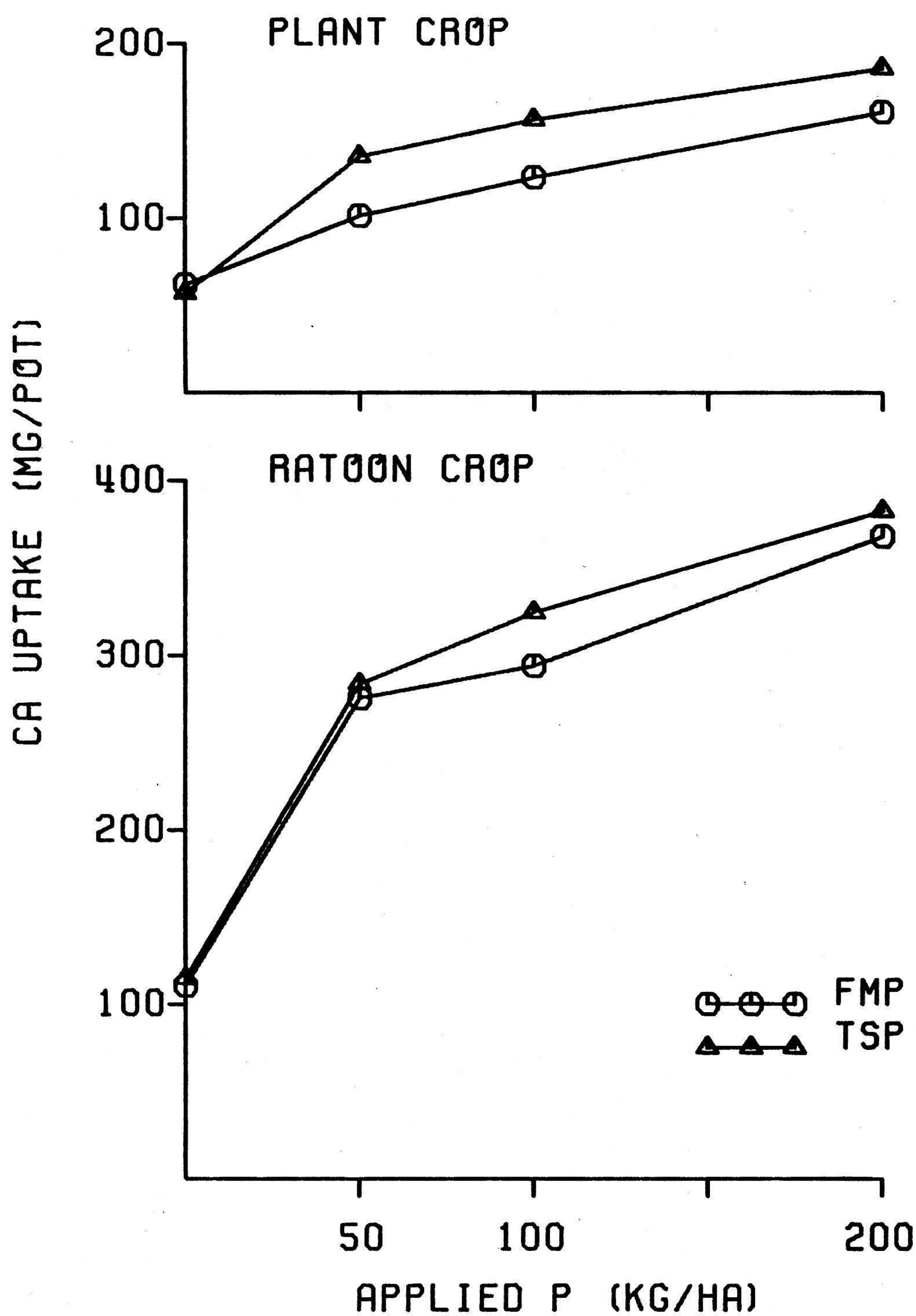

PLANT CROP
RATOON CROP
CA UPTAKE (MG/POT)
200
100
400
300
200
100
50
100
200
APPLIED P (KG/HA)
FMP
TSP

Figure 26. Variation in plant Ca in Sudax with rate and granule size of FMP applied to the Halii soil

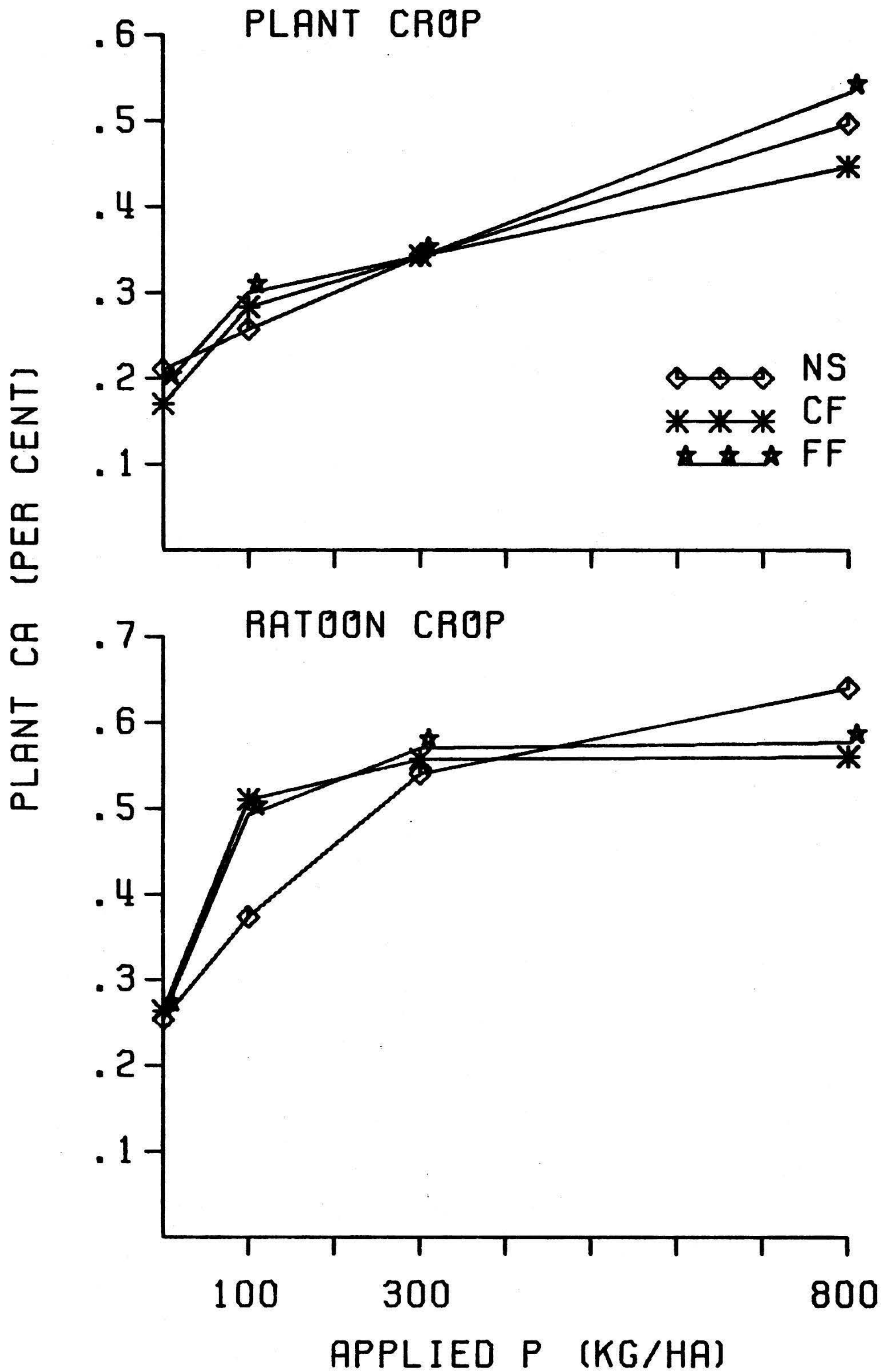
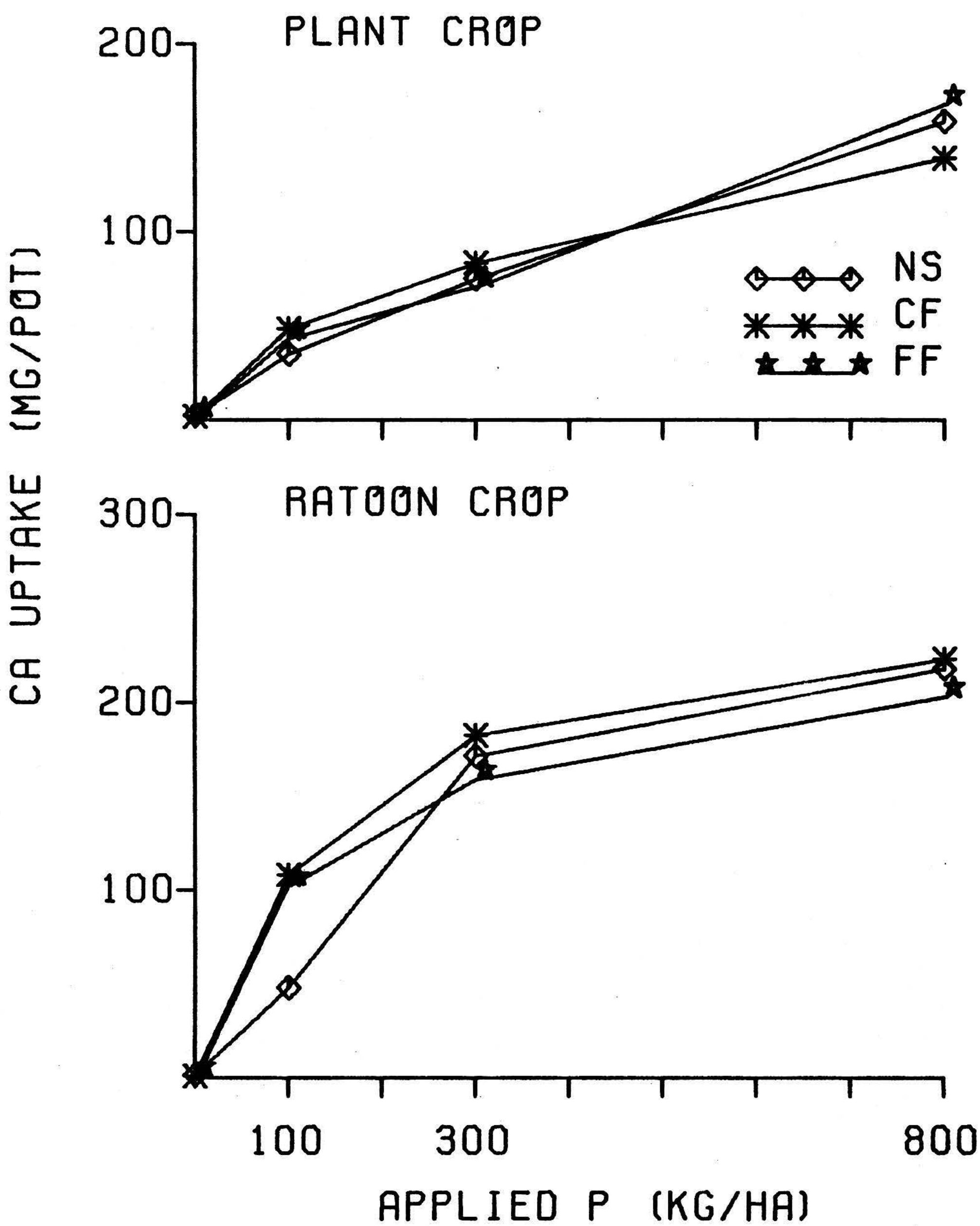

PLANT CROP
RATOON CROP
PLANT CA (PER CENT)
APPLIED P (KG/HA)
NS
CF
FF
.1
.2
.3
.4
.5
.6
.7
100
300
800

Figure 27. Variation in Ca uptake by Sudax with rate and granule size of FMP applied to the Halii soil


PLANT CRØP
200
100
NS
CF
FF
CA UPTAKE (MG/PØT)
RATØØN CRØP
300
200
100
100
300
800
APPLIED P (KG/HA)

These results suggested that Ca solubility in FMP was not affected by the granule size of the material.

Plant K. Average plant K with FMP(NS) was significantly higher than with TSP and TSP + Si in the plant crop (compare 1.71% vs. 1.52 and 1.40%) and the ratoon crop (compare 1.69% vs. 1.33 and 1.38%) in the Halii soil (Appendix Table 28). However, there was no significant difference between the average plant K concentrations with TSP and TSP + Si. When no P was added, average K concentration in the plant crop was 1.64%. This is very close to the critical level of 1.7% K suggested by Chapman (1967) at or below which K deficiency occurs. The plants did not absorb more K due to their poor root systems. With the application of 100 kgP/ha, K concentrations in the plant crop increased significantly to 2.54 and 1.97% with FMP(NS) and TSP, respectively, and did not change much with TSP + Si. In the ratoon crop average plant K concentration at the zero P rate was 1.28%. This indicated K deficiency. When 100 kgP/ha were added, K concentrations increased to 2.54, 1.72 and 1.83% with FMP(NS), TSP and TSP + Si respectively. This suggested that the application of 100 kgP/ha improved the development of efficient root-systems and hence resulted in greater K absorption by plants. However, further applications of P resulted in lowering plant K concentrations in both plant and ratoon crops (Figure 28). This suggested that absorption of K by plants was lowered by the application of higher rates of P. This could be explained by dilution effect and/or competition between K & Ca. Average plant K concentration with FMP(NS) was significantly higher than with TSP and TSP+Si in both harvests. This might be due to the lower dry matter yields with FMP. In the Lualualei soil the application of FMP(NS) as well as TSP lowered plant K concentrations in both plant and ratoon crops (Figure 29). The two sources resulted in comparable plant K values (Appendix Table 29). In the plant crop, K concentrations with both sources were different, but in the ratoon crop, K concentrations with both sources were different. This may be due to depletion of soil K by the bigger plants in the ratoon crop.

Potassium uptake by Sudax from Halii and Lualualei soils is shown in Figures 30 and 31, respectively. Potassium uptake was similar with all forms of P (Appendix Tables 30 and 31).

Tables 9-16 show the analyses of variance.

Figure 28. Variation in plant K in Sudax with rate and source of P applied to the Halii soil

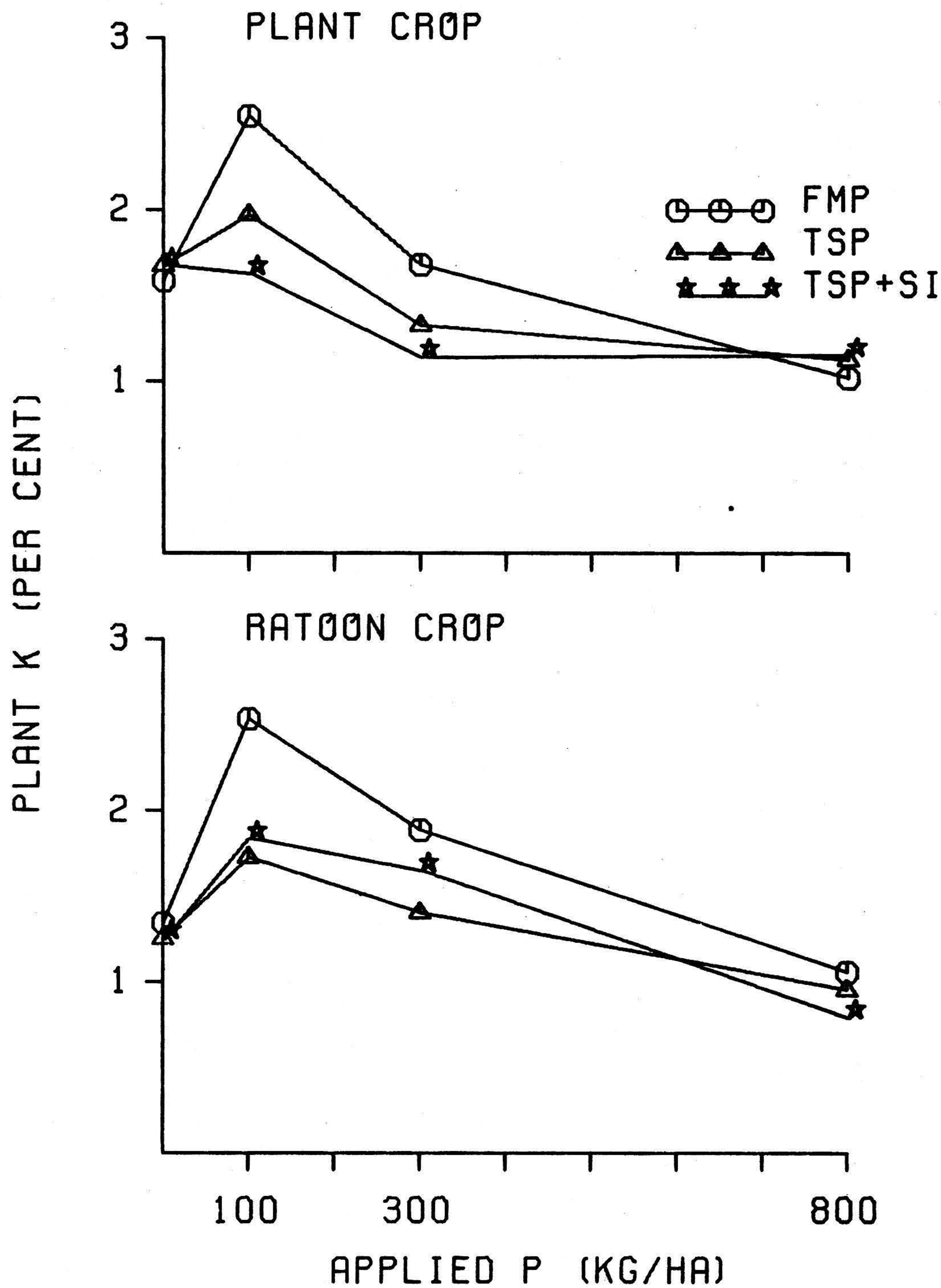

PLANT CROP
RATOON CROP
FMP
TSP
TSP+SI
3
2
1
100
300
800
PLANT K (PER CENT)
APPLIED P (KG/HA)

Figure 29. Variation in plant K in Sudax with rate and source of P applied to the Lualualei soil

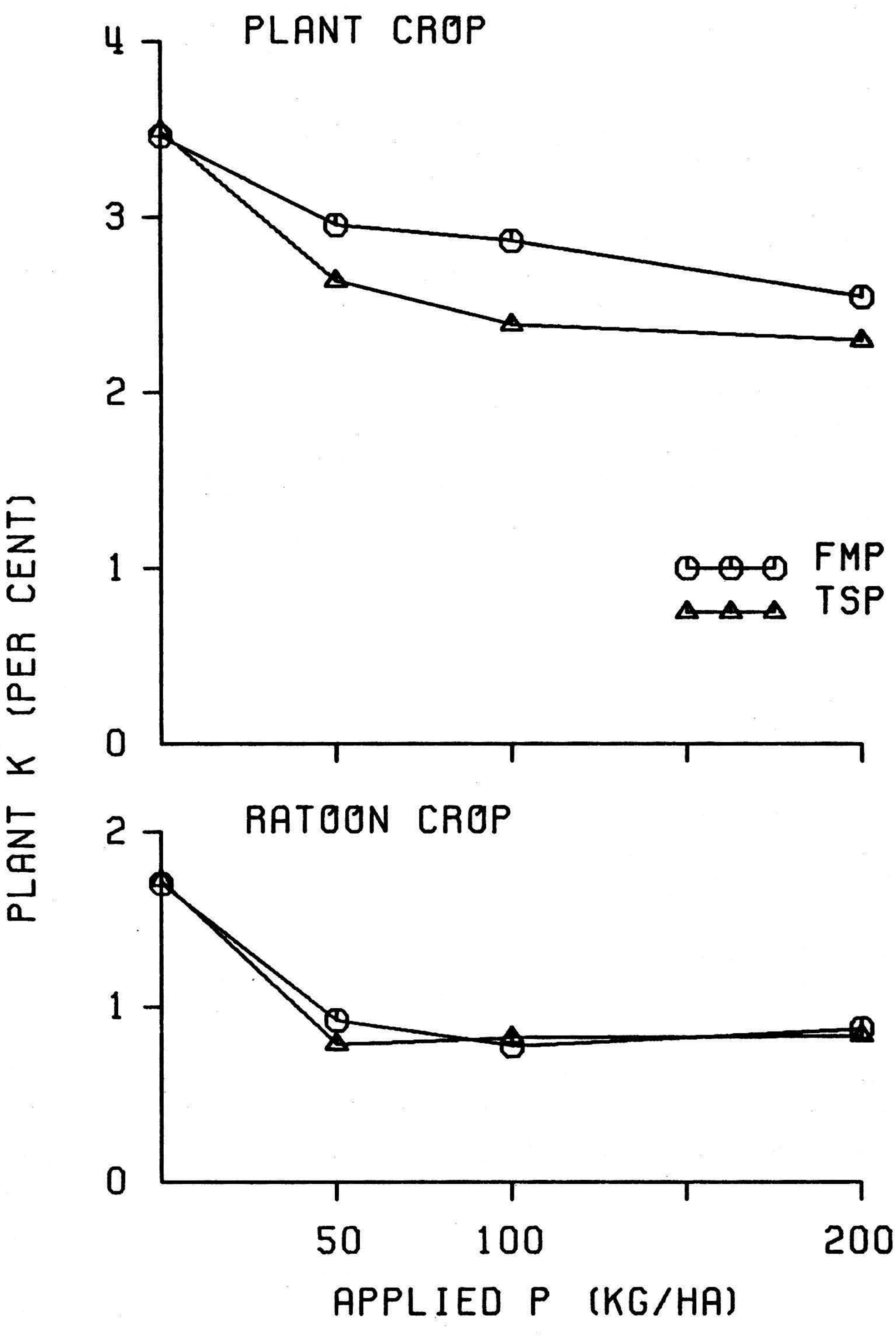

PLANT CROP
RATOON CROP
PLANT K (PER CENT)
APPLIED P (KG/HA)
FMP
TSP
4
3
2
1
0
2
1
0
50
100
200

Figure 30. Variation in K uptake by Sudax with rate and source of P applied to the Halii soil

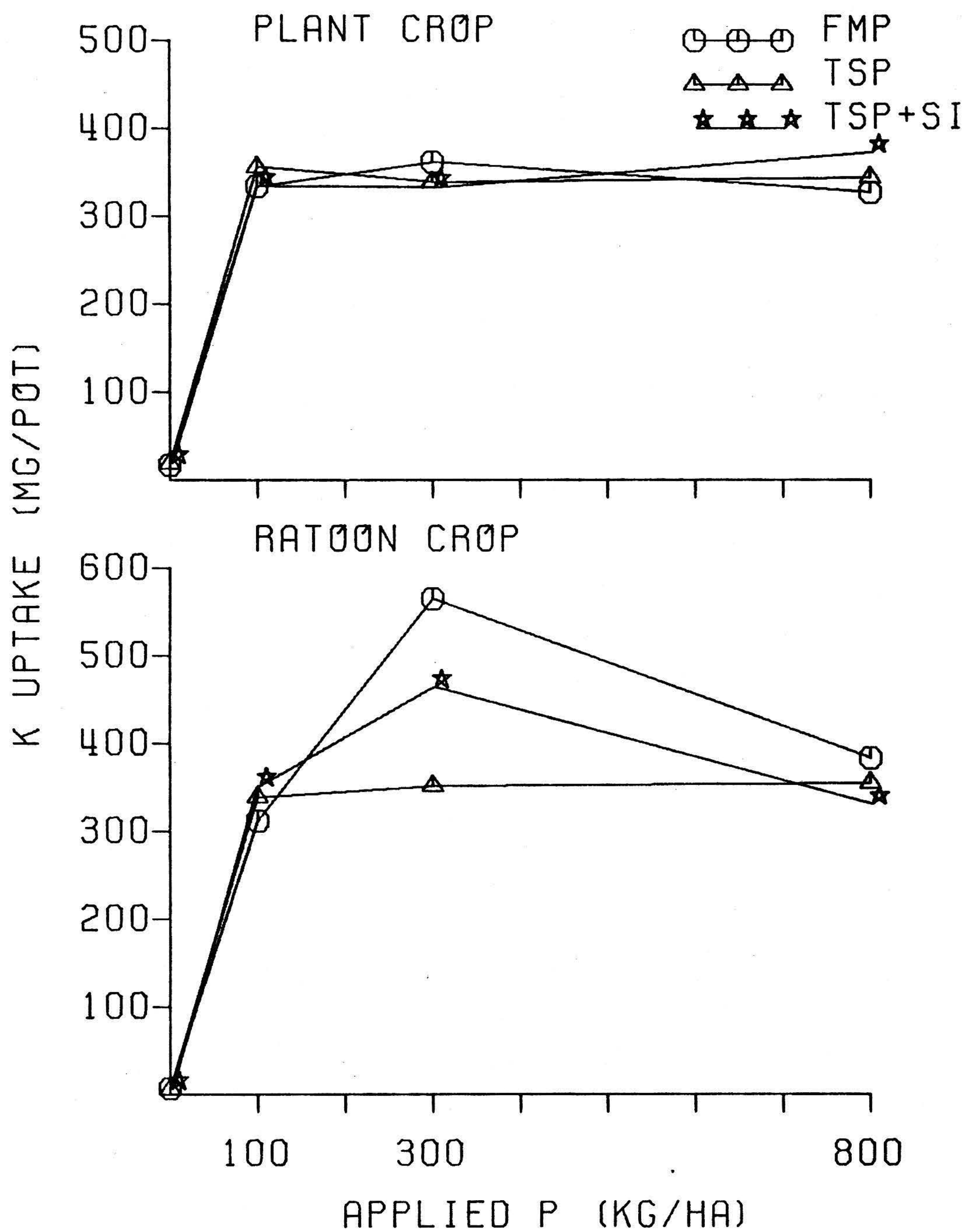

PLANT CROP
FMP
TSP
TSP+SI
500
400
300
200
100
K UPTAKE (MG/POT)
RATOON CROP
600
500
400
300
200
100
100
300
800
APPLIED P (KG/HA)

Figure 31. Variation in K uptake with rate and source of P applied to the Lualualei soil

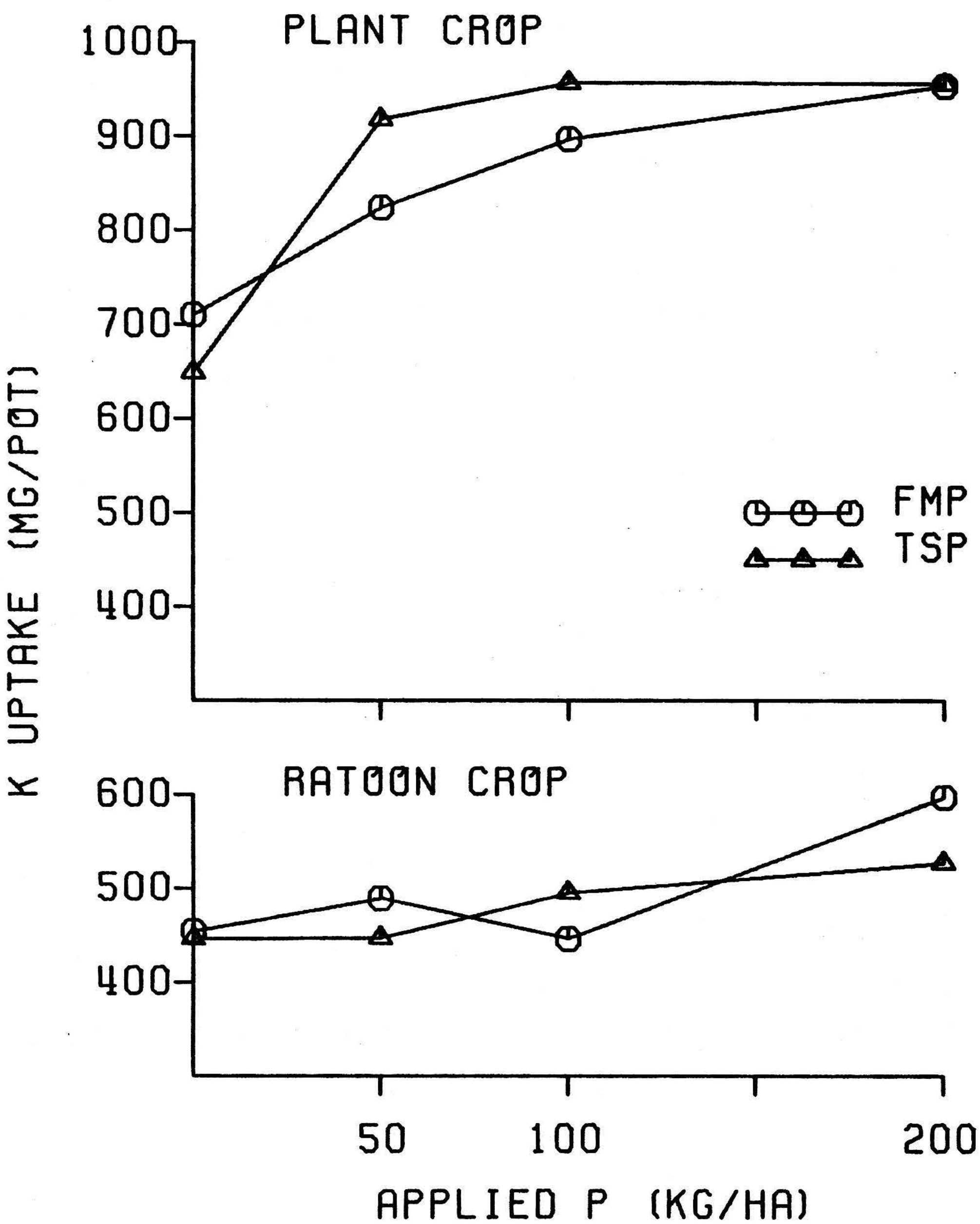

PLANT CROP
RATOON CROP
K UPTAKE (MG/POT)
1000
900
800
700
600
500
400
FMP
TSP
APPLIED P (KG/HA)
50
100
200

Table 9. Analysis of variance of nutrient uptake by the plant crop of Sudax in Source x Rate of P experiment in the Halii soil.

Source of Variance	d.f.+	P	Mg	Si	Ca	K	Mn
		Mean Squares					
Replicates	2	.14	137.93	210.76	203.54	272.82	.39
Treatments	(11)	942.80**	18643.20**	35189.46**	21639.49**	65837.69**	3.01**
Source of P	2	94.66*	2641.37**	28715.04**	12057.90**	90.71	.09
Rate	3	3322.62**	60735.98**	87408.49**	67091.66**	239512.62**	10.38**
Source x Rate	6	35.61*	2930.75**	11238.08**	2107.27**	915.89	.05
Error	19	11.32	311.31	782.53	197.04	610.74	.11
Total	32						

+ D.f. of error term = 22 - 3 = 19 because 3 observations were missing

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 10. Analysis of variance of nutrient uptake by the ratoon crop of Sudax in Source x Rate of P experiment in the Halii soil.

Source of Variation	d.f.+	P	Mg	Si	Ca	K	Mn
		Mean Squares					
Replicates	2	37.51	103.49	1894.57	73.68	15468.08	0.294
Treatments	(11)	1324.83**	34021.79**	73579.17**	50411.49**	86492.61**	2.765**
Source of P	2	37.14	15627.70**	25790.94**	22814.68**	2332.39	0.589*
Rate	3	4756.78**	94622.07**	228140.99**	156864.42**	305437.20**	8.793**
Source x Rate	6	38.08	9853.01**	12227.66**	6383.80**	5073.72	0.476**
Error	15	28.12	457.29	1629.41	1229.82	11401.37	0.120
Total	28						

\+ D.f. of error term = 22 - 7 = 15 because 7 observations were missing

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 11. Analysis of variance of nutrient uptake by the plant crop of Sudax in Source x Rate of P experiment in the Lualualei soil.

Source of Variation	d.f.	P	Mg	Si	Ca	K	Mn
		Mean Squares					
Replicates	2	31.888	471.30	6507.45	57.002	4931.21	0.006
Treatments	(7)	863.709**	12655.17**	29473.80**	6538.258**	43052.25**	0.772**
Source of P	1	8.132	3411.98**	8663.62	2809.088**	3458.88	0.297**
Rate	3	1950.827**	27561.39**	61828.71**	13819.155**	92322.32**	1.651**
Source x Rate	3	61.783	830.00	4055.61	500.416*	6979.96*	0.053*
Error	14	40.485	255.34	2296.76	134.747	2060.30	0.013
Total	23						

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 12. Analysis of variance of nutrient uptake by the ratoon crop of Sudax in Source x Rate of P experiment in the Lualualei soil.

Source of Variation	d.f.	P	Mg	Si	Ca	K	Mn
		Mean Squares					
Replicates	2	48.17	10788.62*	21848.61	2635.77*	2549.63	0.011
Treatments	(7)	1432.27**	84466.45**	363519.64**	33387.35**	8503.27*	0.524**
Source of P	1	65.94	1186.24	1185.26	204.34	1911.56	0.017
Rate	3	3178.52**	188301.80**	796834.69**	75230.76**	15220.96**	0.993**
Source x Rate	3	141.45*	8391.18*	50982.79	2604.93**	3982.81	0.224**
Error	14	41.00	2456.33	16767.29	459.67	2515.19	0.035
Total	23						

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 13. Analysis of variance of dry matter yield and nutrient concentration of the plant crop of Sudax in Granule size x Rate of P experiment in the Halii soil

Source of Variation	d.f.+	Yield	P	Mg	Si	Ca	K	Mn
		Mean Squares						
Replicates	2	1.260	0.00003	0.004	0.003	0.004*	0.087	1873.083**
Treatments	(11)	418.595**	0.00168**	0.122**	0.075**	0.039**	0.744**	162.614
Size of granule	2	6.078	0.00008	0.006	0.108**	0.002	0.170	482.333
Rate of P	3	1518.393**	0.00586**	0.435**	0.176**	0.138**	2.478**	35.509
Size x Rate	6	6.201	0.00012	0.005	0.014	0.001	0.069	119.592
Error	19	4.013	0.00006	0.004	0.012	0.001	0.051	169.675
Total	32							

\+ D.f. of error term = 22 - 3 = 19 because 3 observations were missing. D.f. of yield error term = 22

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 14. Analysis of variance of dry matter yield and nutrient concentration of the ratoon crop of Sudax in Granule size x Rate of P experiment in the Halii soil

Source of Variation	d.f.+	Yield++	P	Mg	Si	Ca	K	Mn
		Mean Squares						
Replicates	2	13.276	0.0001	0.032	0.045	0.009	0.124	175.583
Treatments	(11)	726.295**	0.0031**	0.130	0.168**	0.059**	0.701*	720.917**
Size of granule	2	39.000	0.0014*	0.005	0.049	0.002	0.128	89.083
Rate of P	3	2608.978**	0.0100**	0.373*	0.527**	0.177**	1.980**	2471.435**
Size x Rate	6	14.053	0.0002	0.050	0.029	0.019	0.252	56.269
Error	17	19.419	0.0003	0.075	0.018	0.010	0.290	122.353
Total	30							

+ D.f. of error term = 22 - 5 = 17 because 5 observations were missing

++ D.f. of error for yield is 19

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 15. Analysis of variance of nutrient uptake by the plant crop of Sudax in Granule size x Rate of P experiment in the Halii soil

Source of Variation	d.f.+	P	Mg	Si	Ca	K	Mn
		Mean Squares					
Replicates	2	1.036	406.795	567.988	216.99	931.94	0.535*
Treatments	(11)	573.885**	30316.059**	62812.150**	10592.25**	61829.83**	2.414**
Size of granule	2	2.408	243.045	3563.732	39.50	680.42	0.020
Rate of P	3	2071.541**	109264.088**	223343.665**	38233.67**	225859.03**	8.734**
Size x Rate	6	15.549	866.384	2295.868	289.12	198.37	0.051
Error	19	5.580	322.850	1009.725	104.02	624.06	0.104
Total	32						

\+ D.f. of error term = 22 - 3 = 19 because 3 observations were missing

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 16. Analysis of variance of nutrient uptake by the ratoon crop of Sudax in Granule size x Rate of P experiment in the Halii soil

Source of Variation	d.f.+	P	Mg	Si	Ca	K	Mn
		Mean Squares					
Replicates	2	25.34	1659.57	7491.43	1000.58	17336.13	0.422
Treatments	(11)	1561.58**	62272.38**	103720.40**	22590.50**	68126.11**	1.927**
Size of granule	2	322.35**	3397.48	4190.68	1032.44	644.93	0.132
Rate of P	3	5387.08**	222606.99**	373877.81**	80040.06**	309225.15**	0.462*
Size x Rate	6	61.91*	1730.04	1818.31	1051.73	3070.33	0.256
Error	17	17.41	1726.07	3196.15	728.17	15338.05	0.133
Total	30						

+ D.f. of error term = 22 - 5 = 17 because 5 observations were missing

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Soil Composition

Soil samples collected immediately after harvesting the ratoon crops were analyzed for 0.5M $NaHCO_3$-extractable P, modified Truog-extractable P, sorbed P, water-extractable Si, Neutral NH_4OAc-extractable Mg, Ca, K, Mn, Fe, Cu and Zn, 1N KCl-extractable Al and pH in 1:1 water-soil suspension and 1:1 water-KCl (1N KCl solution) suspension. The effects of rate and form of applied P and granule size of applied FMP on these soil parameters will be discussed.

Extractable Soil P: Soil samples collected after the ratoon crops were analyzed for $NaHCO_3$- and modified Truog-extractable P. Sodium bicarbonate-extractable soil P increased significantly with increasing levels of FMP(NS), TSP and TSP+Si applied to the Halii soil (Tables 17 and 18). Significantly different levels of soil P were extracted with $NaHCO_3$ from the Halii soil fertilized with three forms of P. The highest average level was found with TSP+Si followed by TSP and then FMP(NS) (compare 21.6ppm vs. 16.4 and 12.0 ppm). In the Lualualei soil, a significantly higher level of $NaHCO_3$-extractable soil P was found with TSP than with FMP(NS) (compare 35.0 ppm vs. 30.2 ppm) (Figure 32, Appendix Table 34). This was attributed to the greater solubility of P from TSP than from FMP. Furthermore, the application of $CaSiO_3$ with TSP to the Halii soil increased extractable soil P because the added silicate increased P solubility and reduced the P fixing capacity of the soil.

Table 17. Analysis of variance of Halii soil parameters from the source by rate of P experiment+

Source of Variation	d.f.++	$NaHCO_3$-ext. P	Mod. Truog-ext. P	NH_4OAC-ext. Mg	H_2O-ext. Si	NH_4OAC-extractable Ca	NH_4OAC-extractable K
		Mean Squares					
Replicates	2	8.03	27.03	1.12	0.84	0.25	0.010
Treatments	(11)	242.78**	5160.63**	7.31**	9.11**	4.63**	0.162**
Source of P	2	60.68**	570.86**	2.76*	4.78*	1.20	0.022
Rate of P	3	771.19**	18391.33**	22.41**	22.53**	15.37**	0.521**
Source x Rate	6	39.38**	75.19	1.28	3.94	0.41	0.021
Error	19	7.58	62.28	0.60	0.97	0.10	0.010
Total	32						

\+ Soil samples collected immediately after the ratoon crop.

++ D.F. of error term = 22 - 3 = 19 because 3 observations were missing.

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 17. continued

Source of Variation	d.f.	Mn	Fe	Cu	Zn	KCl-ext. Al	1:1 soil-water pH
		NH_4OAC-extractable					
		Mean Squares					
Replicates	2	0.06	12.72	0.04	1.49	0.025*	0.032
Treatments	(11)	3.60	11.18	2.27**	2.78	0.104**	0.890**
Source of P	2	1.28	5.83	1.52	1.42	0.006	0.011
Rate of P	3	9.30	11.36	2.02**	5.16*	0.363**	3.082**
Source x Rate	6	1.53	12.88	2.65	2.04	0.007	0.061
Error	19	1.72	5.79	0.27	1.05	0.006	0.030
Total	32						

Table 18. Analysis of variance of Lualualei soil parameters from the source by rate of P experiment+

Source of Variation	d.f.	$NaHCO_3$-ext. P	Mod. Truog-ext. P	NH_4OAC-ext. Mg	H_2O-ext. Si	NH_4OAC-extractable Ca	K
		Mean Squares					
Replicates	2	16.79	157.64	1.42	0.103	0.174	0.0002
Treatments	(7)	1377.79**	2389.69**	23.63**	2.201**	1.094**	0.0478*
Source of P	1	140.17*	216.00	69.50**	0.020	0.091	0.0026
Rate of P	3	3106.94**	5402.72**	18.07**	4.532**	2.251**	0.1103**
Source x Rate	3	61.17	101.22	13.90**	0.599	0.271	0.0003
Error	14	19.41	79.64	1.61	0.376	0.201	0.0118
Total	23						

+ Soil samples collected immediately after the ratoon crop.

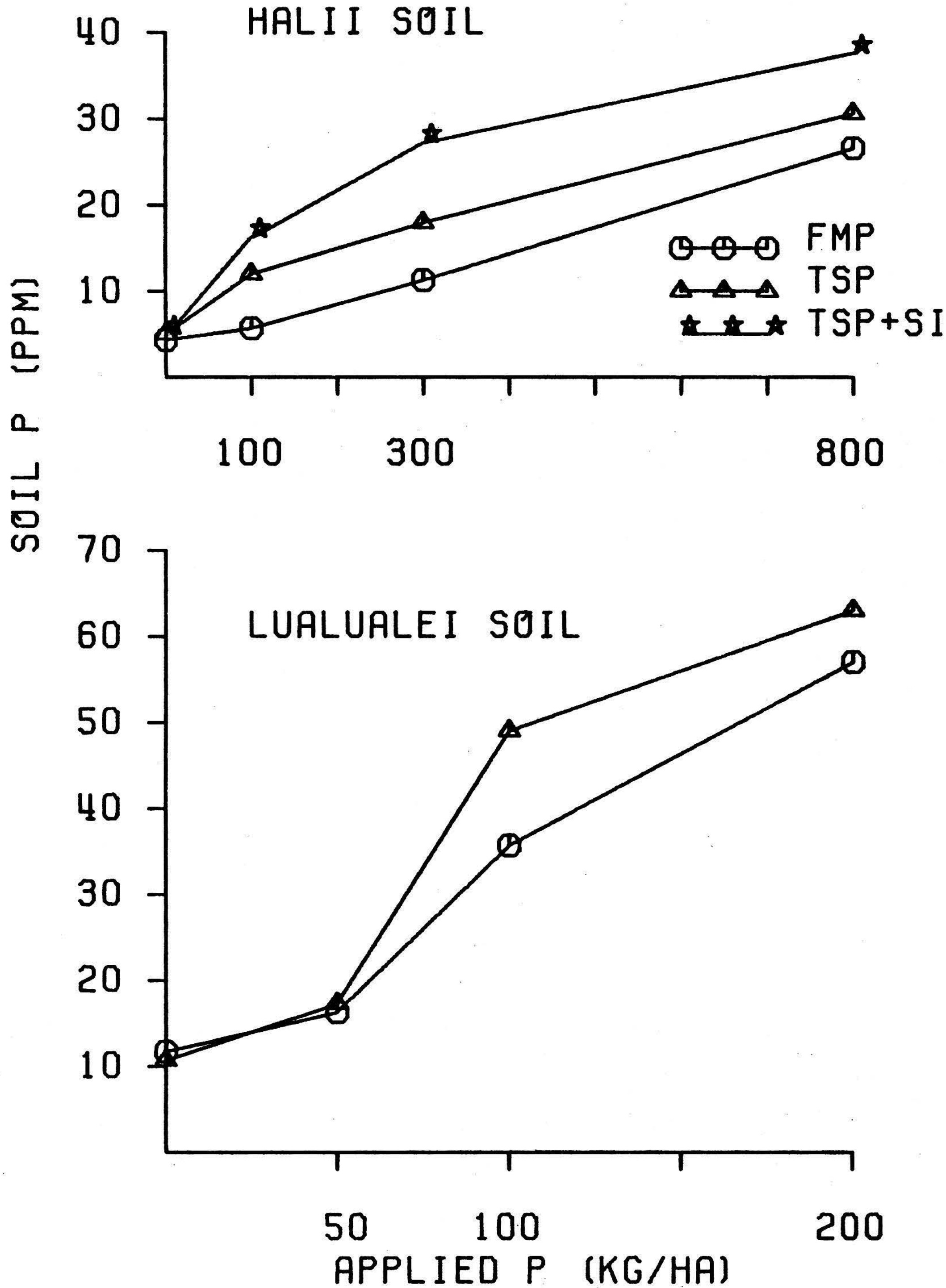
* Significant at the 5% level

** Significant at the 1% level

Table 18. continued

Source of Variation	d.f.		NH4OAC-extractable Mn	Fe	Cu	Zn	1:1 soil-water pH
			Mean Squares				
Replicates	2		53.10	0.07	0.18	0.34	0.014
Treatments		(7)	89.32	0.86*	0.30	3.98**	0.119**
Source of P	1		3.30	1.31*	0.60	6.41*	0.090*
Rate of P	3		120.43	1.07*	0.04	4.46*	0.214**
Source x Rate	3		86.89	0.51	0.47	2.68	0.035
Error	14		36.78	0.26	0.19	0.82	0.015
Total	23						

Figure 32. Variation in 0.5*M*-extractable soil P with rate and source of P applied to Halii and Lualualei soils.


HALII SØIL
40
30
20
10
100
300
800
FMP
TSP
TSP+SI
SØIL P (PPM)
LUALUALEI SØIL
70
60
50
40
30
20
10
50
100
200
APPLIED P (KG/HA)

Significantly different levels of soil P were extracted by $NaHCO_3$ from the Halii soil fertilized with the three granule sizes of FMP (Table 19). The amount of extractable P decreased in the order coarse fraction $>$ normal size $>$ fine fraction (Appendix Table 35). This suggested that the coarse fraction was the least subject to fixation by the soil, and in addition, it was also found to contain slightly higher total P than the other two granule sizes.

Modified Truog-extractable soil P was also significantly different with the three forms of fertilizer P applied to the Halii soil. In the Lualualei soil more soil P was extracted from the TSP than from the FMP treatment but the difference was not significant (Figure 33, Appendix Table 36).

When no P was applied, the two extractants removed more P from the Lualualei soil than from the Halii soil due to the higher level of native P in the former. In both soils the modified Truog-extractant removed more soil P than the $NaHCO_3$. This could be attributed to the different soil:solution ratios of the two extraction procedures. It might also suggest that the modified Truog-extractant dissolved some forms of soil P which were insoluble in $NaHCO_3$. In the laboratory the modified Truog-extractant was found to extract 8% of total P in FMP while $NaHCO_3$ extracted only 0.26% of total P which indicates that the former extractant can remove P from relatively insoluble compounds.

The amount of P extracted by the modified Truog-extractant from the Halii soil was highest for the coarse fraction.

Table 19. Analysis of variance of Halii soil parameters from the granule size by rate of P experiment+

Source of Variation	d.f.++	$NaHCO_3$-ext. P	Mod. Truog-ext. P	NH_4OAC-ext. Mg	H_2O-ext. Hi	NH_4OAC-extractable Ca	NH_4OAC-extractable K
		Mean Squares					
Replicates	2	8.03	27.03	1.12	0.84	0.25	0.012
Treatments	(11)	242.87**	5160.63**	7.31**	9.11**	4.63**	0.157**
Size of Granule	2	70.68**	570.86**	2.76*	4.78*	1.20**	0.017
Rate of P	3	771.19**	18391.33**	22.41**	22.53**	15.37**	0.517**
Size x Rate	6	39.38**	75.19	1.28	3.84**	0.41**	0.024
Error	19	7.58	62.28	0.60	0.97	0.10	0.013
Total	32						

\+ Soil samples collected immediately after the ratoon crop.

++ D.F. of error term = 22-3 = 19 because 3 observations were missing

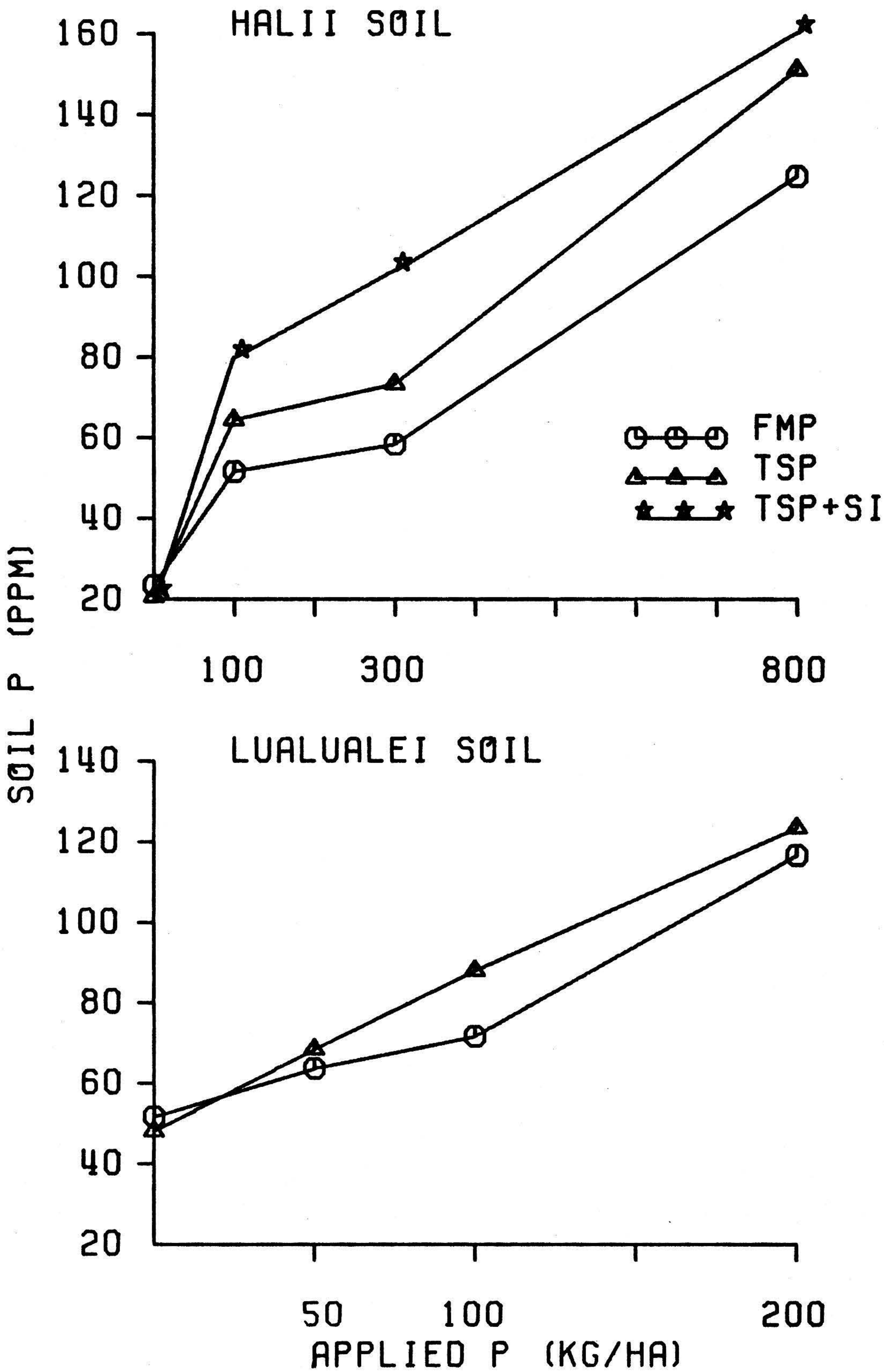
* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 19. continued

Source of Variation	d.f.	NH4OAC-extractable Mn	Fe	Cu	Zn	KCl-ext. Al	1:1 soil-water pH
		Mean Squares					
Replicates	2	0.06	8.45	0.02	1.08	0.025*	0.032
Treatments	(11)	3.60	17.05	1.55**	1.86	0.104**	0.874**
Size of granule	2	1.28	20.01	0.97	1.17	0.006	0.101
Rate of P	3	9.30**	35.94**	0.78	0.67	0.363**	3.084**
Size x Rate	6	1.53	6.62	2.13**	3.00	0.007	0.061
Error	19	1.72	6.12	0.42	1.62	0.006	0.033
Total	32						

Figure 33. Variation in modified Truog-extractable soil P with rate and source of P applied to Halii and Lualualei soils.


HALII SOIL
FMP
TSP
TSP+SI
SOIL P (PPM)
160
140
120
100
80
60
40
20
100
300
800
LUALUALEI SOIL
140
120
100
80
60
40
20
50
100
200
APPLIED P (KG/HA)

P in the coarse fraction was the least subject to fixation, followed by P in the normal fraction and then P in the fine fraction.

Sorbed P: Phosphate sorption curves were constructed for soil samples collected after harvesting the ratoon crops. The Halii soil samples showed that the amount of P sorbed at 0.05 ppm P in solution was lower when TSP + Si was applied than when FMP or TSP were applied (Figures 34-36, Appendix Table 38). This indicated that the application of Si reduced P sorption. Silva (1971) reported that silicate applied to soil at 500 ppm Si decreased P sorption by some Hawaiian soils, and Khalid (1974) found that residual Si reduced P sorption by the Halii soil. Less P was sorbed at 800 kgP/ha than at 100 and 300 kgP/ha. There was less P sorption with application of TSP + Si at all three rates of P which indicates this combination resulted in greater solubility of added P during the two crops and thus more P available to the plants. The consistently higher amounts of P sorbed in the FMP treatment reflect its lower solubility than the other two forms of P. Figure 37 shows the P sorption curves for the Halii soil when 0, 100, 300 and 800 kgP/ha were applied as FMP(NS) and the curve for the Lualualei soil when no P was added. The curves for the Halii soil shift to the right as the amount of applied P increases indicating a reduction in the amount of sorbed P.

Figure 34. P sorption curves of the Halii soil fertilized with 100 Kg P/ha as FMP(NS), TSP and TSP+Si.

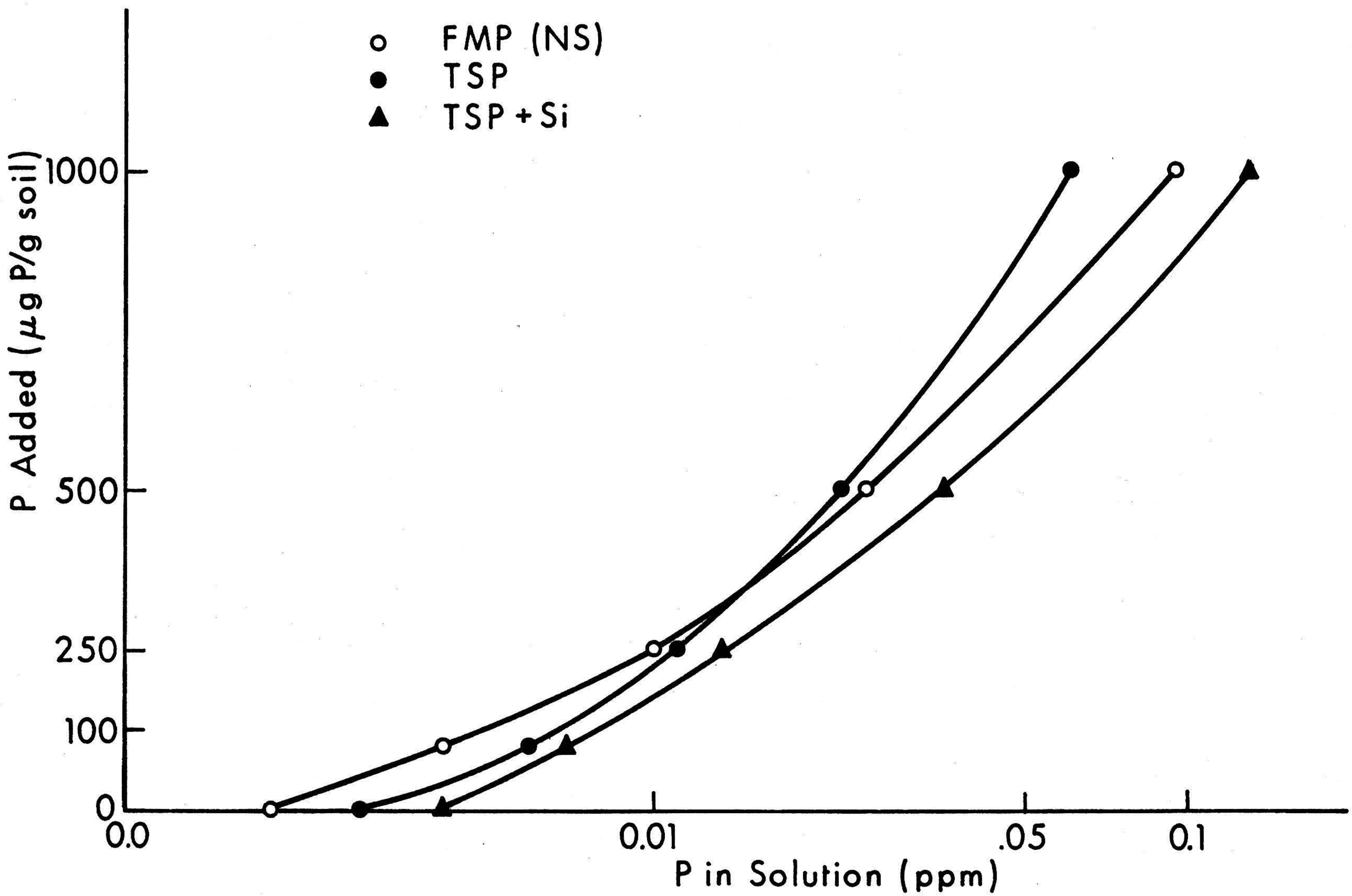

FMP (NS)
TSP
TSP + Si
P Added (μg P/g soil)
1000
500
250
100
0
0.0
0.01
.05
0.1
P in Solution (ppm)

Figure 34. P sorption curves of the Halii soil fertilized with 300 Kg P/ha as FMP(NS), TSP and TSP+Si.

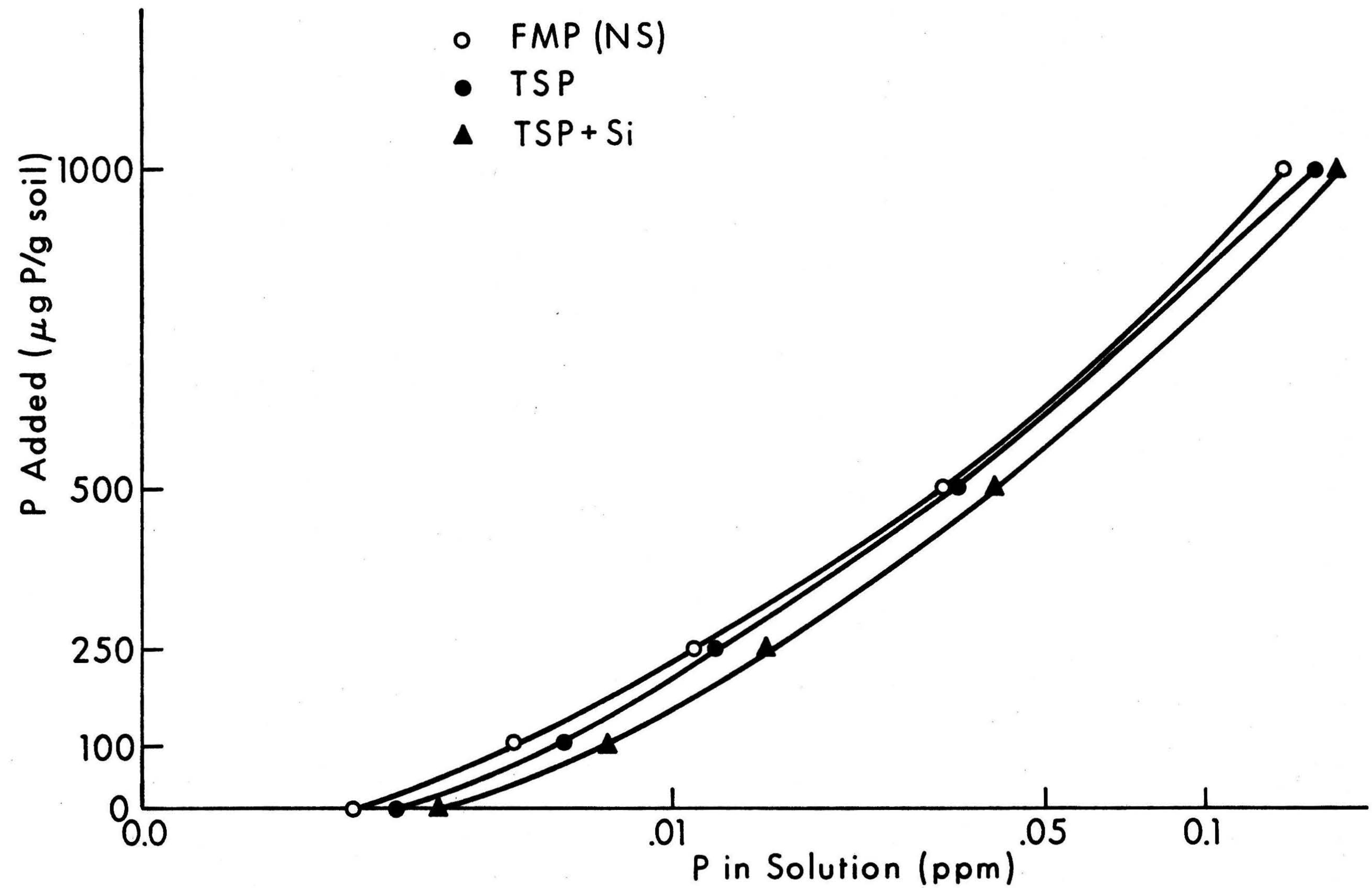
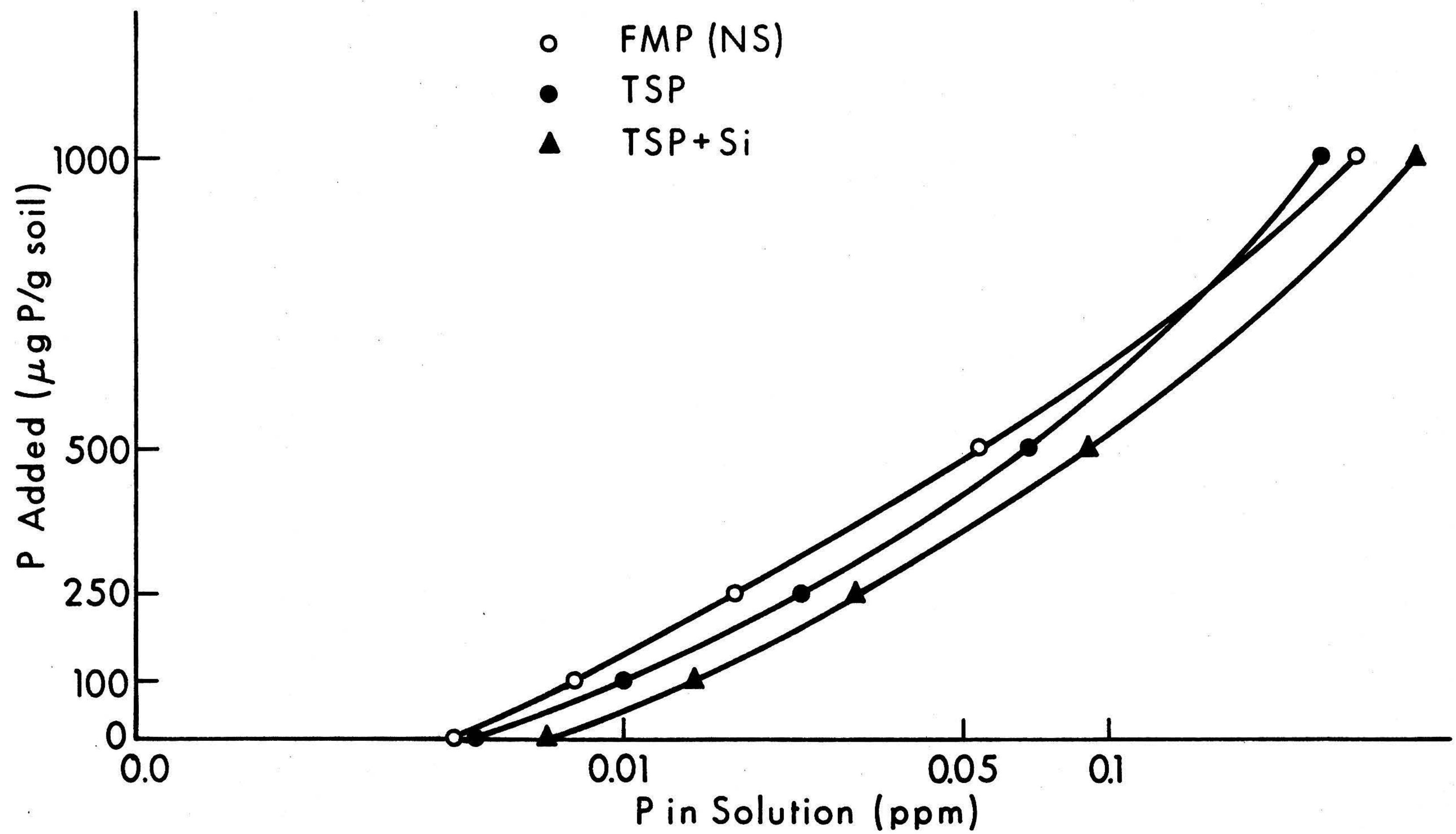
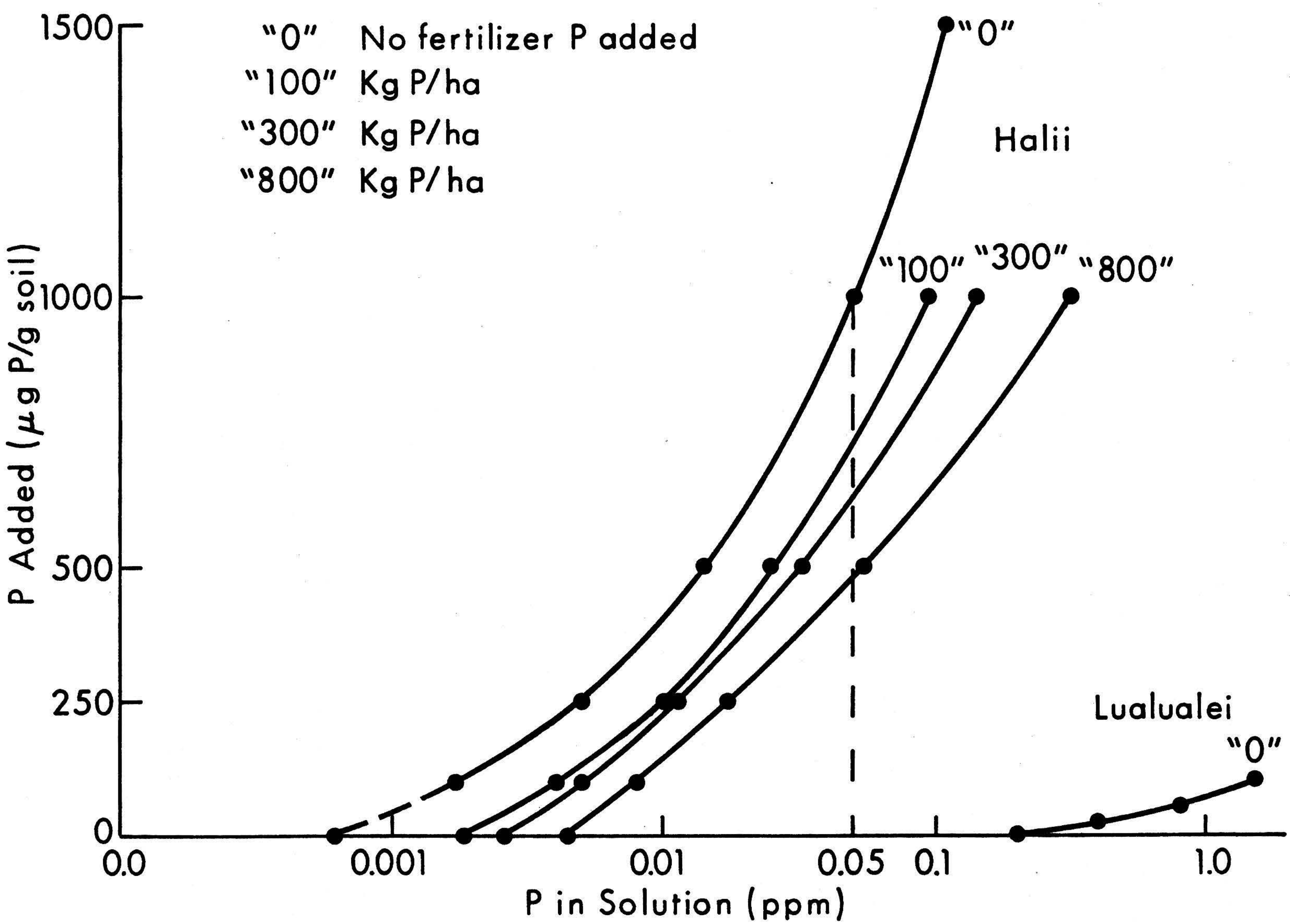

FMP (NS)
TSP
TSP + Si
P Added (μg P/g soil)
1000
500
250
100
0
0.0
.01
.05
0.1
P in Solution (ppm)

Figure 36. P sorption curves of the Halii soil fertilized with 800 Kg P/ha as FMP(NS), TSP and TSP+Si.



FMP (NS)
TSP
TSP + Si
1000
500
250
100
0
P Added (µg P/g soil)
0.0
0.01
0.05
0.1
P in Solution (ppm)

Figure 37. P sorption curves of the Halii soil fertilized with different levels of P applied as FMP(NS).

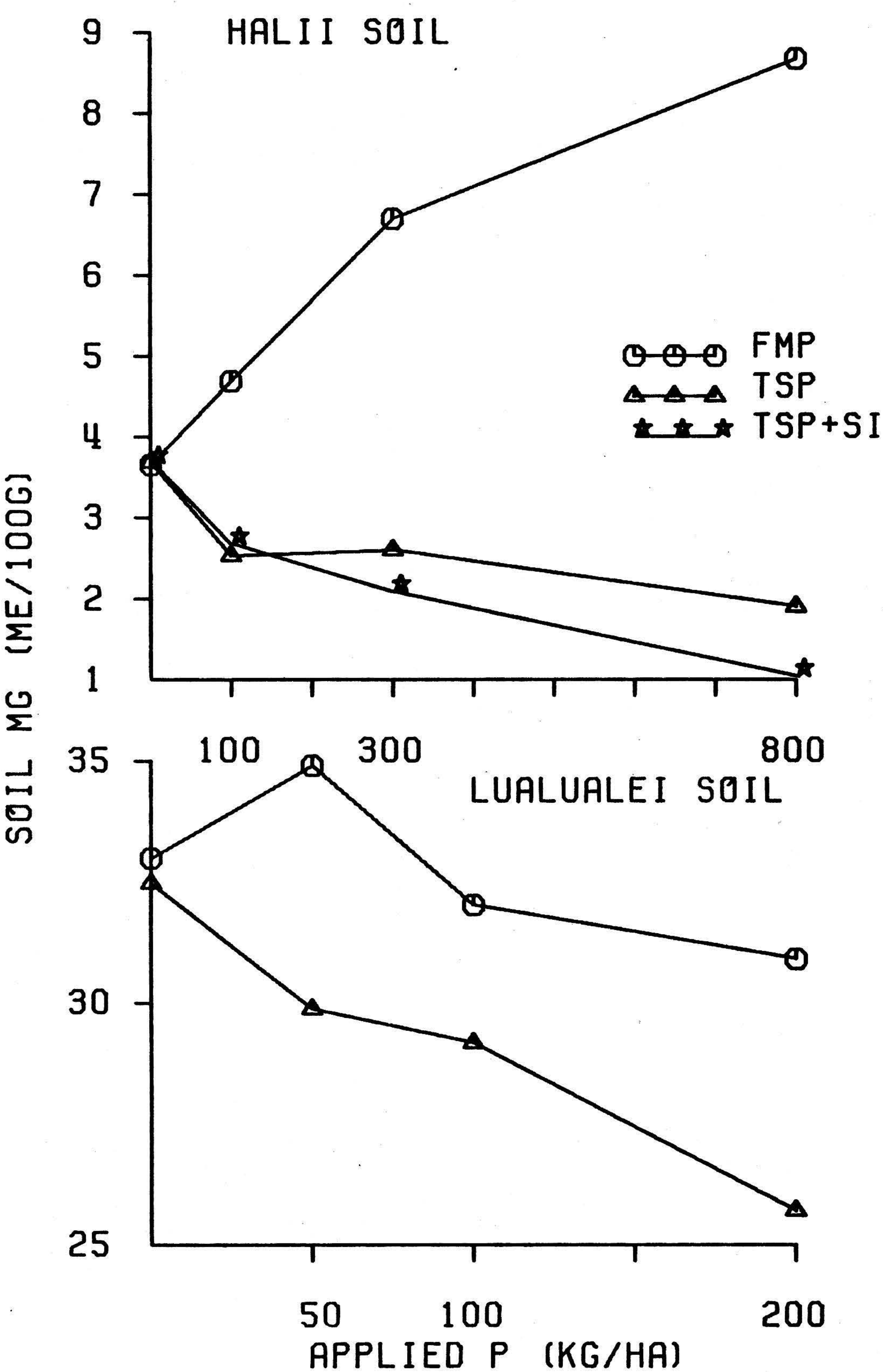

"0" No fertilizer P added
"100" Kg P/ha
"300" Kg P/ha
"800" Kg P/ha
1500
1000
500
250
0
P Added (μg P/g soil)
"0"
Halii
"100"
"300"
"800"
Lualualei
"0"
0.0
0.001
0.01
0.05
0.1
1.0
P in Solution (ppm)

The particle size of FMP had no effect in P sorption by the Halii soil (Appendix Table 38).

Soil Mg: Neutral ammonium acetate-extractable soil Mg increased significantly with increasing amounts of FMP(NS) applied to the Halii soil, but decreased with increasing amounts of TSP and TSP + Si (Figure 38). Average soil Mg was significantly higher with FMP(NS) than with TSP and TSP + Si (compare 5.9 me/100 g soil vs. 2.7 and 2.4 me/100 g soil) (Appendix Table 39). This was attributed to the fact that FMP(NS) contains 9% Mg. The decrease of soil Mg with increasing amounts of TSP and TSP + Si was possibly due to depletion of soil Mg by bigger plants. In the Lualualei soil, extractable Mg decreased with increasing amounts of both FMP(NS) and TSP. Average soil Mg was significantly higher with FMP(NS) than with TSP (compare 32.7 vs. 29.3 me/100 g soil). The Lualualei soil is very rich in Mg and applications of up to 200 kgP/ha as FMP(NS) did not affect the Mg status of the soil. Nevertheless, the level of soil Mg dropped with increasing amounts of applied FMP(NS) and TSP due to soil Mg depletion by larger plants.

Comparable levels of soil Mg were found with applications of normal size (NS) and coarse fractions (CF) of FMP, while significantly lower levels occurred with fine fraction (FF) (compare 5.9 and 6.2 me/100 g soil vs. 5.3 me/100 g soil) (Appendix Table 40). This suggested that

Figure 38. Variation in NH_4OAc-extractable soil Mg with rate and source of P applied to Halii and Lualualei soils.



HALII SØIL
FMP
TSP
TSP+SI
SØIL MG (ME/100G)
9
8
7
6
5
4
3
2
1
100
300
800
35
30
25
LUALUALEI SØIL
50
100
200
APPLIED P (KG/HA)

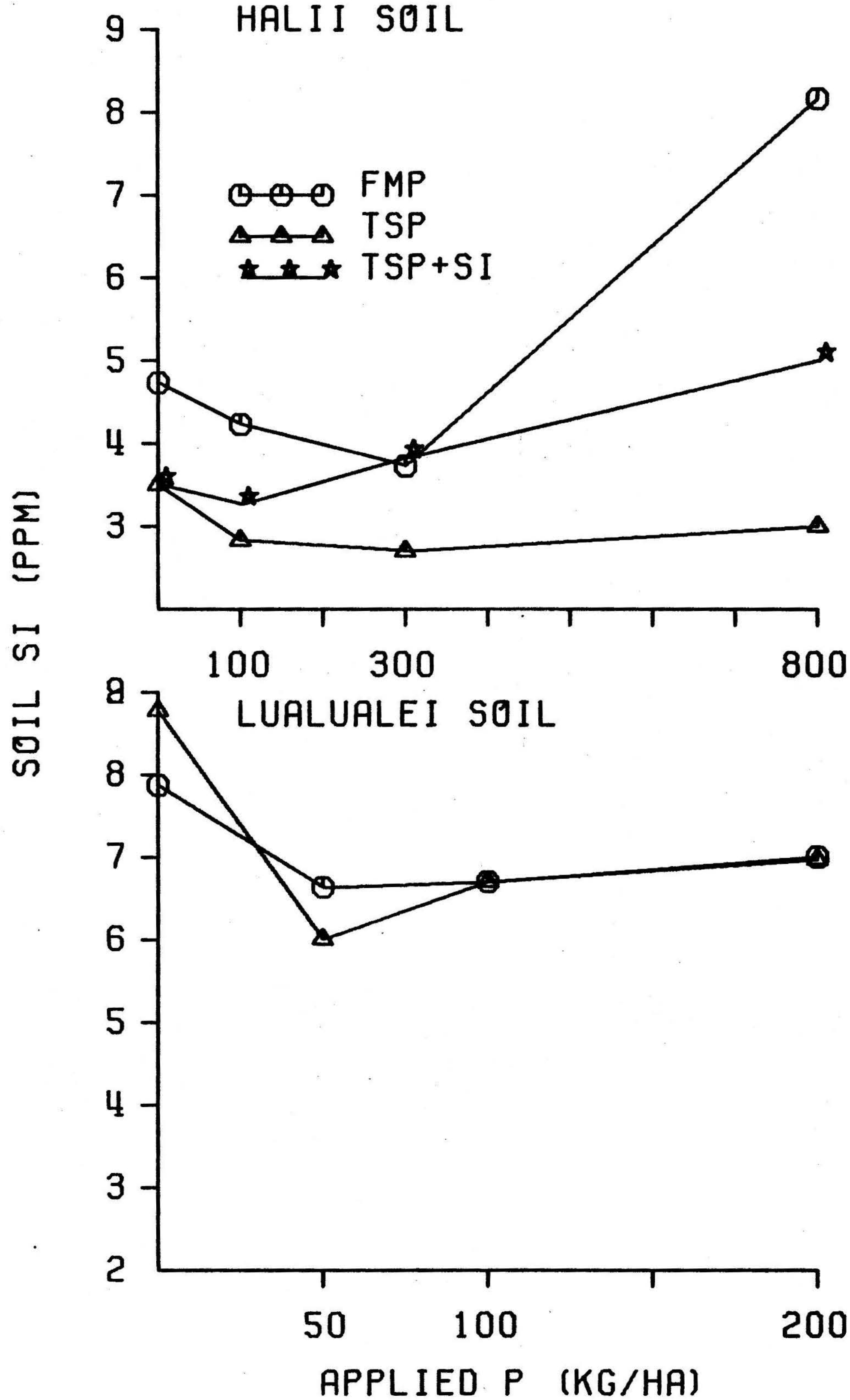
Mg in the fine fraction of FMP was more subject to leaching than Mg in the other two granule sizes.

Soil Si: Increasing levels of applied P as FMP(NS) or TSP + Si did not increase Si solubility in the Halii soil samples except with the application of 800 kgP/ha. Levels of water-extractable soil Si were relatively constant with increasing amounts of TSP (Figure 39). Average soil Si was highest with FMP(NS) followed by TSP + Si and then TSP (compare 5.2 ppm vs. 3.9 and 3.0 ppm) (Appendix Table 41). Both FMP(NS) and TSP + Si added Si to the soil. In the Lualualei soil average soil Si was the same for FMP(NS) and TSP (7.1 ppm).

Soil Si levels observed are a result of several factors including Si uptake by plants, leaching of Si in the profile and Si fixation by the soils. The water-extractable soil Si levels observed in both soils were higher than normal because the irrigation water contained 30 ppm Si.

Average soil Si was nearly the same for the normal size and coarse fraction of FMP applied to the Halii soil (compare 5.2 ppm vs. 5.1 ppm), but was significantly lower for the fine fraction (4.1 ppm) (Appendix Table 42). This may be explained by two points: (1) Si and P in the fine fraction were more readily fixed by the Halii soil than Si and P in the other two granule sizes due to the greater

Figure 39. Variation in water-extractable soil Si with rate and source of P applied to Halii and Lualualei soils.


HALII SØIL
FMP
TSP
TSP+SI
9
8
7
6
5
4
3
100
300
800
LUALUALEI SØIL
9
8
7
6
5
4
3
2
50
100
200
SØIL SI (PPM)
APPLIED P (KG/HA)

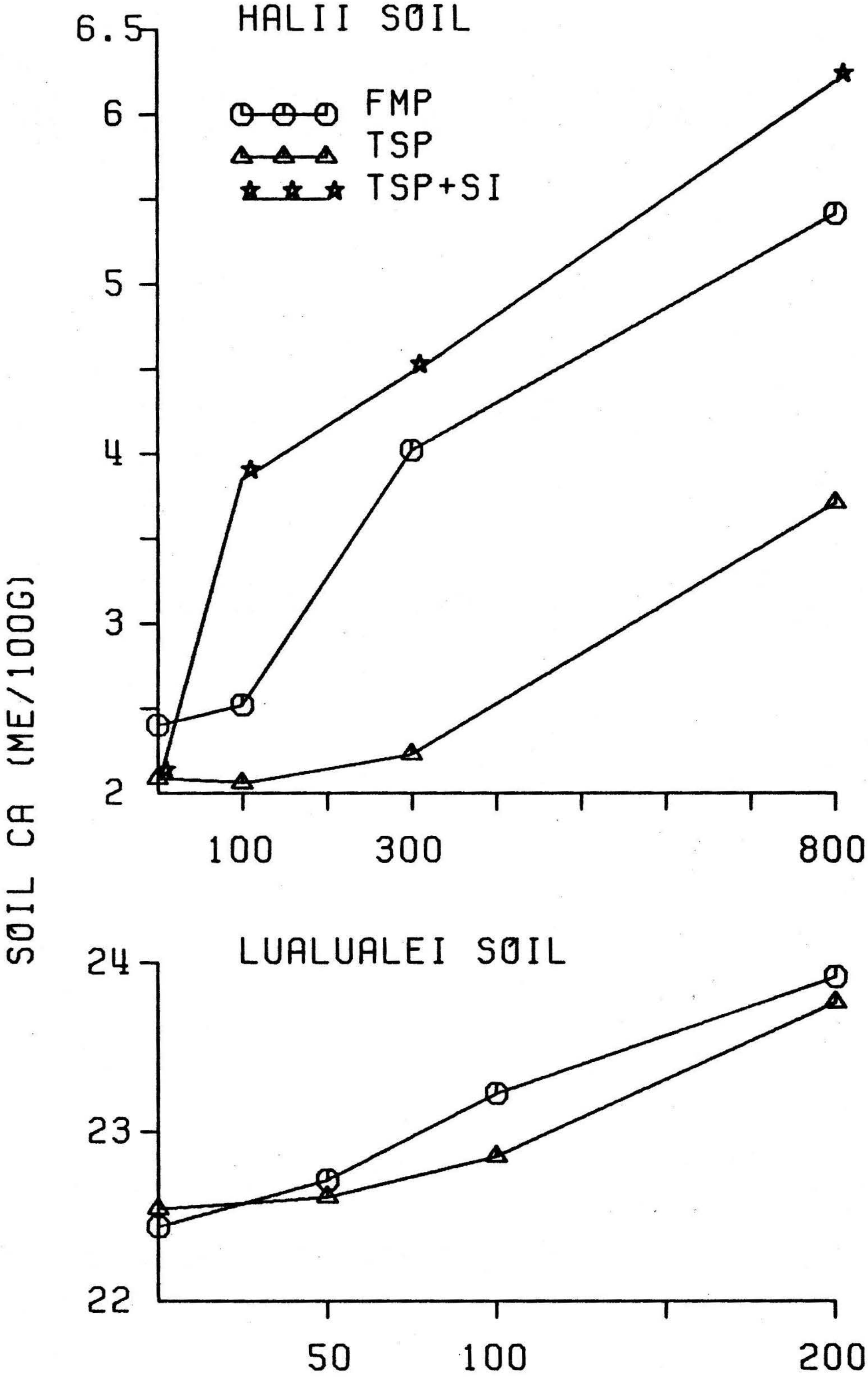
solubility of the material, thus applied P did not contribute much to the reduction of Si fixation; and/or (2) Si was more readily leached through the soil.

<u>Soil Ca</u>: Neutral ammonium acetate-extractable soil Ca increased with increasing amounts of fertilizer P applied to both soils (Figure 40). In the Halii soil average soil Ca was highest with TSP + Si followed by FMP(NS) and then TSP (compare 4.2 me/100 g soil vs. 3.6 and 2.5 me/100 g soil). However, the difference between TSP + Si and FMP(NS) was not significant at the 5% level (Appendix Table 43). They both added more Ca to the soil than TSP. In the Lualualei soil the levels of extractable soil Ca were high and average soil Ca was nearly the same for FMP(NS) and TSP (23.1 and 22.[illegible] me/100 g soil).

The three granule sizes of FMP applied to the Halii soil behaved quite similarly in supplying Ca to the soil at the highest rate of applied P (800 kgP/ha), but differently at the other two rates. When 100 and/or 300 kgP/ha were applied, extractable soil Ca was highest for the normal size fraction treatment, followed by the coarse fraction and then the fine fraction (Appendix Table 44).

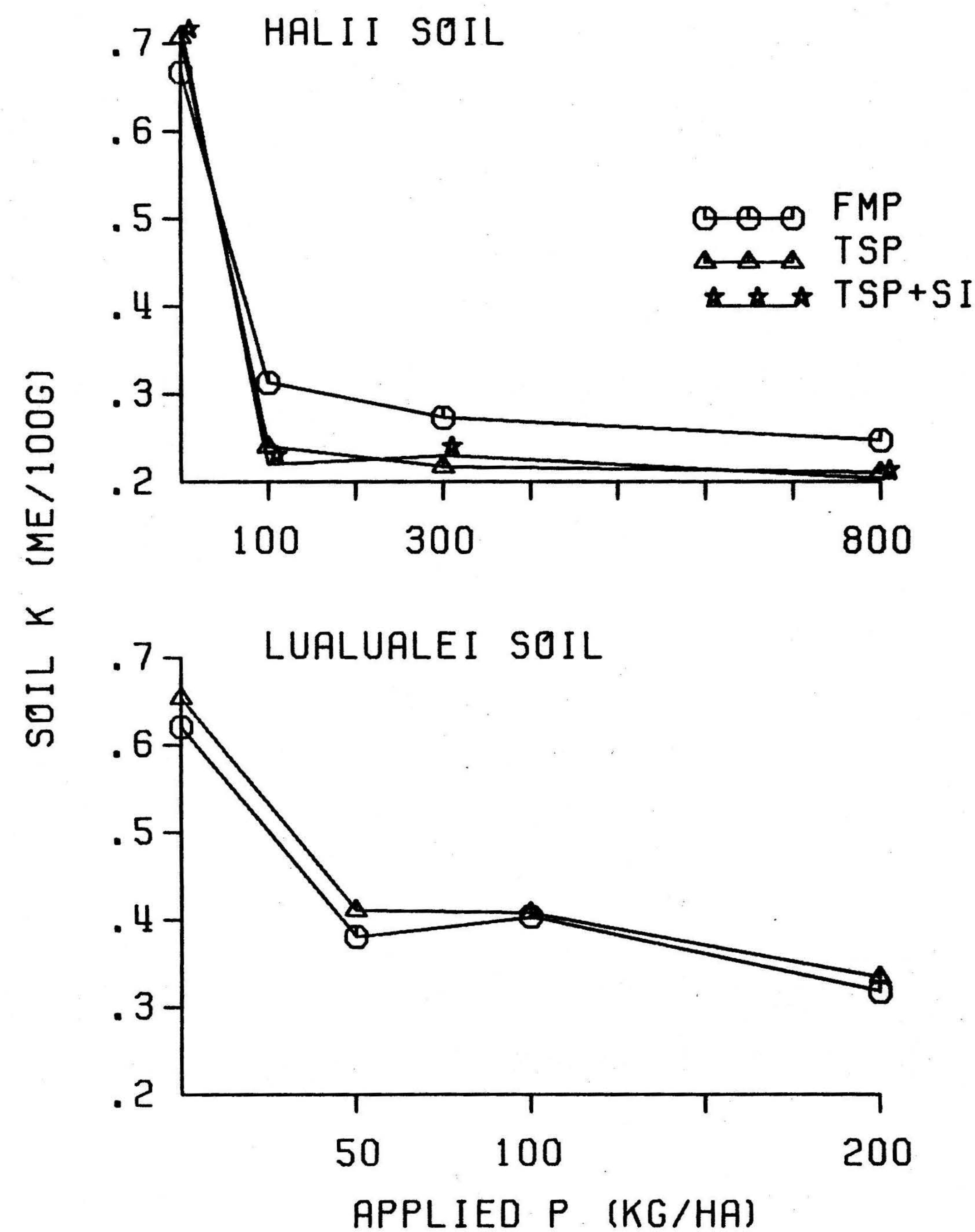
<u>Soil K</u>: Neutral ammonium acetate-extractable soil K was almost identical for the different forms of P applied to both Halii and Lualualei soils (Appendix Table 45, Figure 41). The very low levels of soil K can probably

Figure 40. Variation in soil Ca with rate and source of P applied to Halii and Lualualei soils.



HALII SØIL
FMP
TSP
TSP+SI
6.5
6
5
4
3
2
100
300
800
SØIL CA (ME/100G)
LUALUALEI SØIL
24
23
22
50
100
200

Figure 41. Variation in soil K with rate and source of P applied to Halii and Lualualei soils.


HALII SOIL
LUALUALEI SOIL
SOIL K (ME/100G)
APPLIED P (KG/HA)
FMP
TSP
TSP+SI
.7
.6
.5
.4
.3
.2
100
300
800
50
100
200

be explained by high leaching rates and crop removal. There was also no difference among the soil K levels for the three granule sizes of FMP applied to the Halii soil (Appendix Table 46).

Soil pH: Soil pH values were determined after harvesting the ratoon crops. In both soils, pH values increased with increasing levels of applied P (Tables 17 and 18, Figure 42 and 43). In the Halii soil the three forms of P behaved differently at different rates. At the 100 kgP/ha rate TSP + Si resulted in the highest soil pH value while TSP and FMP(NS) had nearly similar values (compare 4.9 vs. 4.6 and 4.5). At the 300 kgP/ha rate, soil pH values were nearly the same for the three forms. With the application of 800 kgP/ha, FMP(NS) resulted in the highest pH value followed by TSP + Si and then TSP (compare 5.6 vs. 5.3 and 5.0) (Appendix Table 47). The higher Ca levels and the presence of Si in FMP and TSP + Si, as compared to TSP, are the explanation for the higher pH levels associated with them. However, the mean soil pH values for the three materials were not significantly different at the 5% level (Appendix Table 47). In the Lualualei soil, pH values were higher with FMP than with TSP (Appendix Table 47). This is again attributed to Si and higher Ca level in FMP.

Soil pH values for the three granule sizes of FMP

Figure 42. Variation in soil pH with rate and source of P applied to the Halii soil.

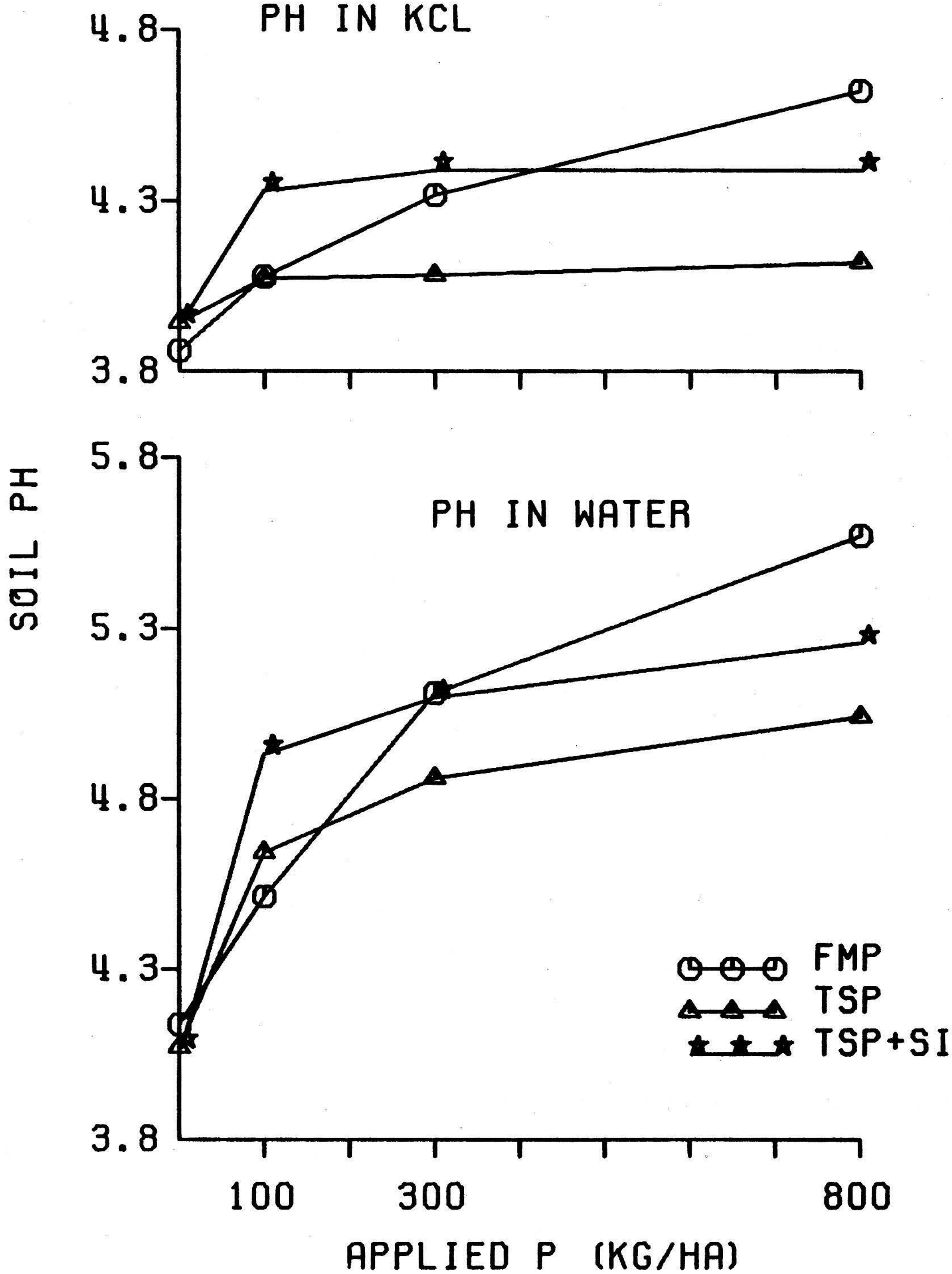
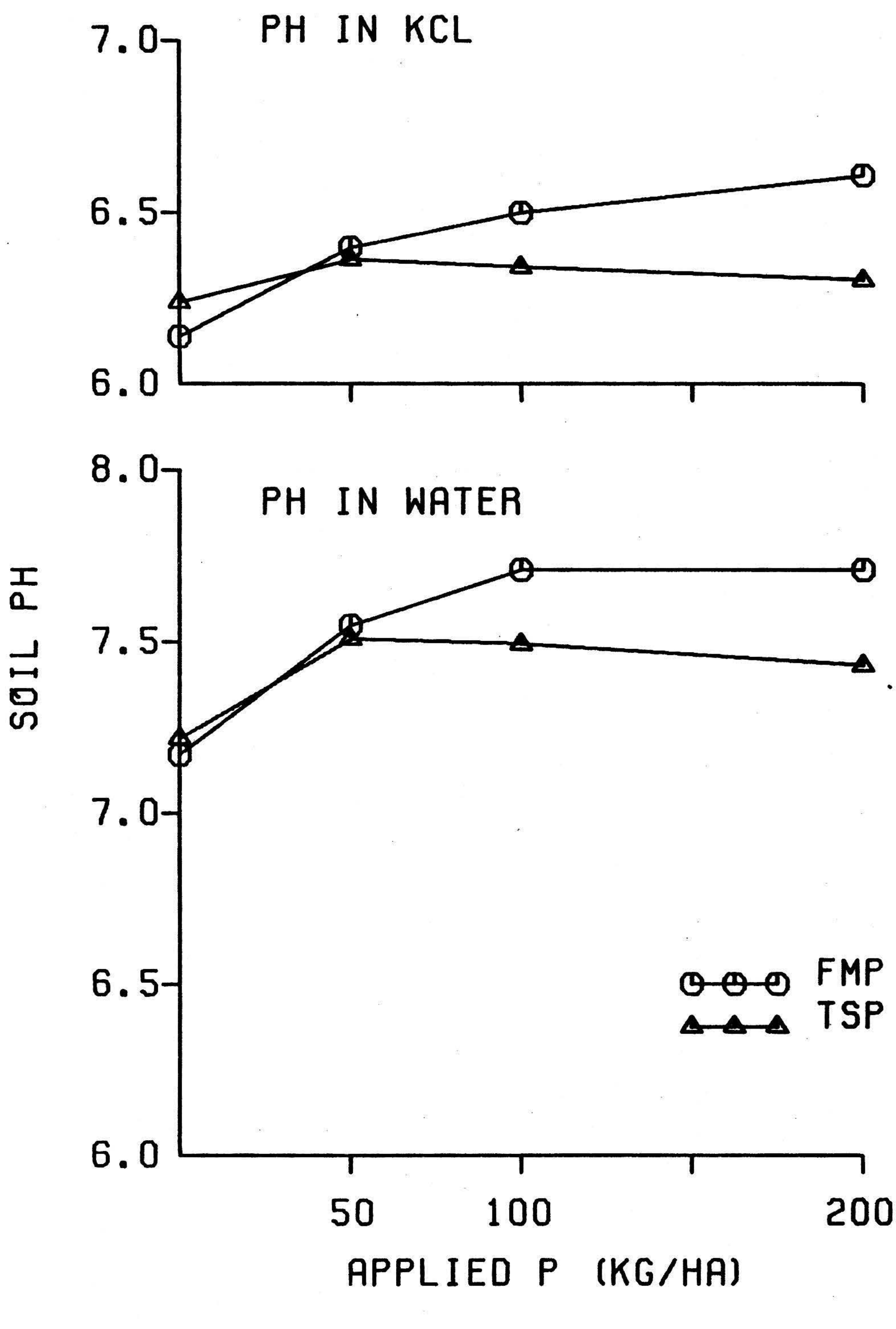

PH IN KCL
4.8
4.3
3.8
SOIL PH
5.8
PH IN WATER
5.3
4.8
4.3
3.8
FMP
TSP
TSP+SI
100
300
800
APPLIED P (KG/HA)

Figure 43. Variation in soil pH with rate and source of P applied to the Lualualei soil.


PH IN KCL
7.0
6.5
6.0
8.0
PH IN WATER
SØIL PH
7.5
7.0
6.5
6.0
FMP
TSP
50
100
200
APPLIED P (KG/HA)

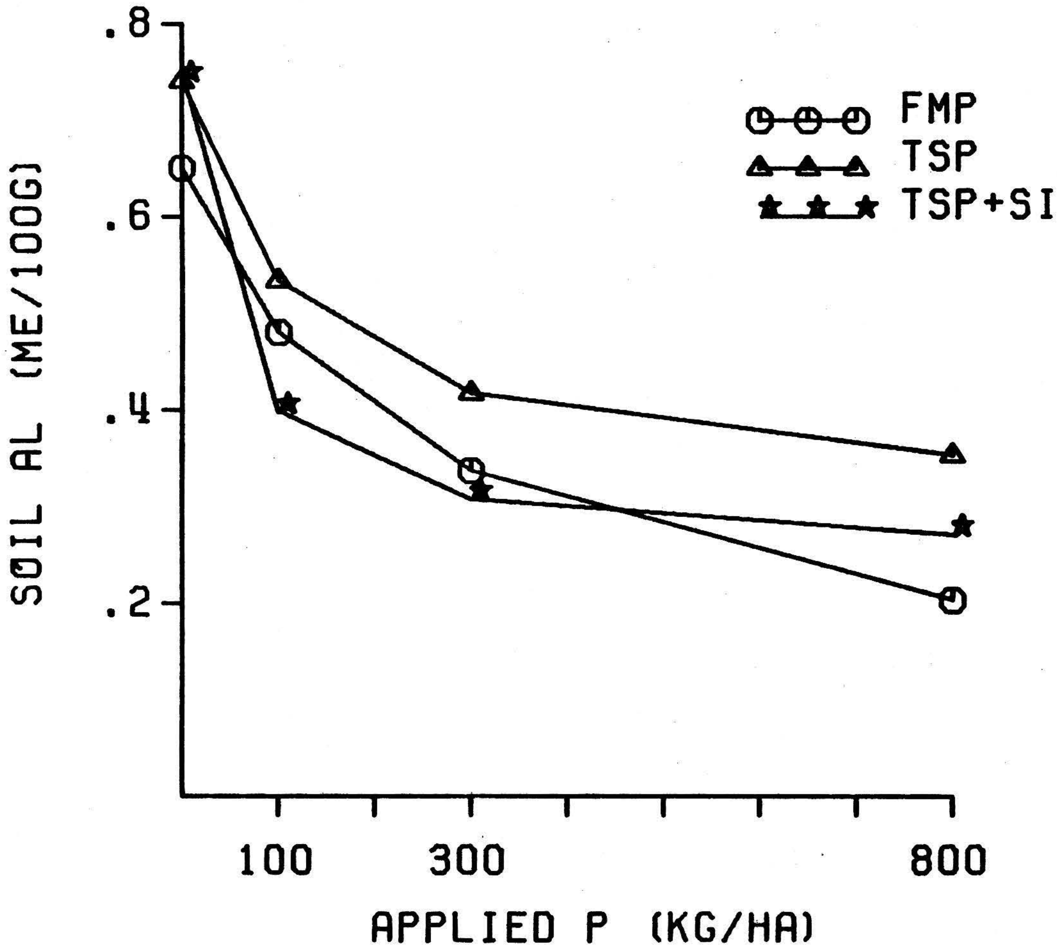
applied to the Halii soil were nearly the same (Appendix Table 48).

Soil Al: Aluminum was extracted with 1N KCl solution from Halii soil samples after harvesting the ratoon crop. Highly significant decreases in extractable Al were observed with increasing levels of applied P (Table 17, Figure 44). The application of fertilizer P rich in Ca increased the level of adsorbed Ca which resulted in higher pH and hence lower Al activity. Soil Al levels were nearly the same for the different forms of fertilizer P (Appendix Table 49).

The granule size of FMP had no effect on soil Al. Soil Al values for the three sizes applied were nearly the same (Appendix Table 48).

Neutral 1N NH_4OAc-extractable soil Mn, Fe, Cu and Zn did not vary considerably for neither the different sources of P applied to Halii and Lualualei soils nor the different granule sizes of FMP applied to the Halii soil.

Figure 44. Variation in 1N KCl-extractable soil Al with rate and source of P applied to the Halii soil.



.8
.6
.4
.2
SOIL AL (ME/100G)
FMP
TSP
TSP+SI
100
300
800
APPLIED P (KG/HA)

SUMMARY AND CONCLUSIONS

Dry matter yields of plant and ratoon crops of Sudax increased with increasing amounts of fertilizer P in both the Halii and the Lualualei soil. Treble superphosphate gave significantly higher average dry matter yields in the plant crop than FMP in the two soils. This was explained by the greater water solubility of TSP. However, in the ratoon crops average dry matter yields were nearly identical with TSP and FMP in both soils. The availability of P, and other nutrients, in FMP increased with time as the fertilizer material was gradually dissolved by the weak acid formed in the soil and on the surface of the plant roots. On the other hand, P in TSP was fixed by the soils due to its high solubility.

The application of calcium silicate to the Halii soil with TSP increased dry matter yields of both plant and ratoon crops, but the increase was not significant. The availability of soil and fertilizer P and the supply of Ca increased with $CaSiO_3$ addition.

Dry matter yields in the two soils were higher in the ratoon crops than in the plant crops. This was attributed to the more efficient root systems of the ratoon crops.

Similar dry matter yields were produced by the three granule sizes of FMP applied to the Halii soil.

Plant P concentrations were similar for FMP, TSP and TSP+Si in the Halii soil and for FMP and TSP in the Lualualei soil. Plant Si was highest with FMP in the Halii soil. This suggested that FMP might have a stimulating effect on Si absorption.

Soil analysis showed that the level of soil P was significantly higher for TSP than FMP in both soils. The addition of $CaSiO_3$ with TSP caused significantly higher soil P. Added Si probably increased the solubility of fertilizer and soil P and reduced the P fixing tendency of the soil.

The modified Truog extractant removed more P from soils than did $NaHCO_3$. This suggested that the former dissolved some forms of soil P which were insoluble in the latter. The greater water:soil ratio of the modified Truog extractant probably also resulted in increased P extraction.

The amounts of soil P extracted from the Halii soil with the three granule size treatments increased in the order fine fraction $<$ normal size $<$ coarse fraction. This was attributed to the slightly higher total P content in the coarse fraction. It also showed that P in the CF was the least subject to fixation by the soil.

Phosphorus sorption studies revealed that P sorbed by the Halii soil from the three fertilizer materials was in the order TSP+Si $<$ TSP $<$ FMP. In the Lualualei soil the order was TSP $<$ FMP.

Fused magnesium phosphate increased soil pH from 4.1 to 5.6 in the Halii soil and from 7.5 to 7.7 in the Lualualei soil with the applications of 800 and 200 Kg P/ha to the two soils, respectively. The same amount of fertilizer material reduced the level of soil Al in the Halii soil from 0.7 to 0.2 me/100 g soil.

Fused magnesium phosphate appears to be a suitable P fertilizer for highly weathered soils with high P fixing capacity and low pH. In addition, soils low in Si, Mg, or Ca would also benefit from this material. Some upland Hawaiian soils have such characteristics.

Appendix A

Soil Analytical Methods

Extraction Procedures

Modified Truog-extractable Phosphorus: Soil P was extracted by the modified Truog method of Ayres and Hagihara (1952).

Two grams of soil (oven dry basis) and 200 ml of 0.02$\underline{N}$ H_2SO_4 containing 3 grams of ammonium sulfate per liter were placed in a 500-ml Erlenmeyer flask. A small amount of activated carbon (DARCO G-60) was added to the soil-extractant mixture. The flask and its contents were shaken for 30 minutes. The suspension was filtered using Whatman No. 42 filter paper, and P was determined colorimetrically with the phosphomolybdenum blue method of Dickman and Bray (1940) using a Technicon Autoanalyzer.

Sodium Bicarbonate-extractable Phosphorus: Soil phosphorus was extracted with the sodium bicarbonate method of Olsen *et al* (1954). Five grams of soil (oven dry basis) was shaken with 100 ml of 0.5$\underline{M}$ $NaHCO_3$ solution (pH 8.5) and 1 teaspoon of carbon black for 30 minutes. The suspension was then filtered through Whatman No. 40 filter paper, and P was determined by the Dickman and Bray (1940) method on a Technicon Autoanalyzer.

Water-extractable Silicon: Three grams of soil (oven dry basis) was placed with 30 ml of distilled water in a 50-ml polypropylene centrifuge tube and shaken in a reciprocal shaker for four hours. Some of the suspension was centrifuged at 14,000 rpm for 10 minutes. The Si in the supernatant was determined colorimentrically with the silico-molybdate blue method of Kilmer (1965).

KCl-extractable Aluminum: Ten grams of soil (oven dry basis) was shaken with 100 ml of 1N KCl solution for 90 minutes and filtered in a Buchmer funnel. The volume of the extract was made to 100 ml and Al was determined with the titration method of Yuan (1959).

Phosphorus Sorption Studies

Phosphorus sorption curves were constructed for each treatment on soil samples composited over replications using the procedures of Fox and Kamprath (1970). Three-gram soil samples (oven dry basis) were equilibrated for 6 days at 25^{o}C in 30 ml of 0.01 M $CaCl_2$ solution containing serial concentrations of P. Three drops of toluene were added to inhibit microbial growth. Equilibration was carried out in 50-ml polyproplyne centrifuge tubes which were shaken horizontally in a mechanical shaker for 30 minutes twice daily, morning and evening. After centrifugation in a super-speed centrifuge, P was determined colorimetrically in the supernatant with the phosphomolybdenum blue method of Dickman and Bray (1940) on a Technicon Autoanalyzer, and phosphate sorbed was calculated by difference. Phosphate sorbed was plotted against phosphate remaining in solution on Semilog paper. Values of P sorbed at 0.05 ppm P in solution were taken as measure of phosphate requirement of the crop. The slopes of the curves show the phosphate buffering capacity of the soil, and the intercept at zero phosphate sorbed indicates the original P intensity in the soil.

Chemical Methods

Soil Phosphorus: Soil P was determined colorimetrically as phosphomolybdenum blue on a Technicon Autoanalyzer with the Molybdenum Blue method of Dickman and Bary (1940). A suitable aliquot was pipetted in a 50-ml volumetric flask and diluted to volume with distilled water.The 2 ml phosphorus analyzer sample cup was filled with solution and placed in position #1. The sample tray holds 40 samples which can be run in an hour. Ammonium molybdate and diluted stannous choloride solutions were prepared and supplied to the Autoanalyzer for color development. Optical density was recorded on a chart and the amount of phosphate present was calculated from the chart.

Fertilizer Phosphorus: Total P in three granule sizes of fused magnesium phosphate was determined colorimetrically as phosphomolybdenum in a Junior Spectrophotometer with the Ascorbic Acid method of Watanabe and Olsen (1965). A suitable aliquot was pipetted into a 25-ml. volumetric flask and distilled water was added to make volume to 20 ml. Then 4 ml. of reagent B was added and the sample was made to volume with distilled water. The contents were mixed and P concentrations were determined in a Junior Spectrophotometer with a wavelength set at 700 mu.

Soil Silicon: Soil Si was determined colorimetrically by the Silico-molybdate Blue method of Kilmer (1965). A suitable aliquot (1-10 ml) of the water extract was transferred to a 50-ml volumetric flask and diluted to about 35 ml with distilled water. One ml of ammonium molybdate solution was added with mixing. The color was allowed to develop for 30 minutes, and then 3 ml of 10% oxalic acid solution was added to destroy the phosphorus color complex. Within two minutes after the addition of oxalic acid, 1 ml of reducing solution (1-amino, 2-naphtol, 4-sulfonic acid) was added with mixing and the sample was made to volume with distilled water. Color was allowed to develop for 30 minutes, and then absorbance was read with Klett-Summerson colorimeter using filter No. 40.

Soil Aluminum: Exchangeable Al in soils was determined by the titration method of Yuan (1959). The filtrate of the 1*N* KCl extraction was titrated with 0.1 *N* standard NaOH solution after adding 10 drops of 0.1% phenophthalein. The milliequivalents of alkali used was recorded as exchangeable acidity. One drop of 0.1*N* HCl was added to bring the solution back to colorless, and 10 ml of 4 percent KF was added with stirring. The solution was titrated with 0.1*N* HCl to just colorless. The milliequivalents of acid used was considered as exchangeable Al.

Fertilizer Material Analytical Methods

Extraction Procedure:

Total Phosphorus Extraction: Total phosphorus in fused magnesium phosphate was extracted by aqua regia (Hill *et al*, 1948). One g. sample was dissolved in 10 ml HNO_3 and 30 ml HCl. After cooling, the solution was transferred to 500 ml volumetric flask, diluted to volume, mixed and filtered through Whatman No. 40. Four ml of the filtrate was pipetted into a 100 ml volumetric flask and diluted to volume. The amount of phosphorus in the fertilizer material was determined colorimetrically by the method of Watanabe and Olsen (1965), in a Junior Spectrophotometer.

APPENDIX B

TABLES OF DATA

Table 1. Influence of rate and source of P applied to the Halii soil on dry matter yield of Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP (NS)	1.1[a]	13.6[a]	21.7[a]	32.0[a]	17.1[a]	0.5[a]	12.3[a]	30.9[a]	38.5[a]	20.6[a]
TSP	1.1[a]	18.1[b]	26.3[b]	30.7[a]	19.1[b]	0.5[a]	19.7[b]	25.3[b]	37.4[a]	20.7[a]
TSP with Si	1.1[a]	20.6[c]	29.3[c]	32.3[a]	20.8[b]	0.5[a]	19.4[b]	28.3[c]	42.1[b]	22.6[a]
TSP with Mg			25.4[b]					26.1[b]		

* Means of 3 reps expressed as g/pot

** Means of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability

Table 2. Influence of rate and source of P applied to the Lualualei soil on dry matter yield of Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	20.5^{a}	28.2^{a}	31.6^{a}	37.5^{a}	29.5^{a}	27.3^{a}	53.6^{a}	57.4^{a}	68.1^{a}	51.6^{a}
TSP	18.6^{a}	35.1^{b}	40.1^{b}	41.8^{b}	33.9^{b}	25.0^{a}	56.7^{a}	60.2^{a}	63.3^{b}	51.4^{a}

* Means of 3 reps expressed as g/pot

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 3. Influence of rate and granule size of FMP applied to the Halii soil on dry matter yield of Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS+	1.1^{a}	13.6^{a}	21.7^{a}	32.0^{a}	17.1^{a}	0.5^{a}	12.3^{a}	30.9^{a}	38.5^{a}	20.6^{a}
CF++	1.1^{a}	17.2^{a}	24.4^{a}	30.9^{a}	18.4^{a}	0.3^{a}	19.9^{b}	35.7^{b}	40.2^{a}	24.0^{a}
FF+++	1.0^{a}	14.5^{a}	20.6^{a}	32.8^{a}	17.2^{a}	0.5^{a}	17.7^{b}	31.9^{a}	35.6^{b}	21.4^{a}

* Means of 3 reps expressed as g/pot

** Means of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability

\+ Normal size

++ Coarse fraction

+++ Fine fraction

Table 4. Influence of rate and source of P applied to the Halii soil on P concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	0.06^a	0.10^a	0.12^a	0.12^a	0.10^a	0.07^a	0.12^a	0.13^a	0.14^a	0.12^a
TSP	0.06^a	0.08^a	0.10^a	0.16^b	0.10^a	0.07^a	0.10^a	0.13^a	0.13^a	0.11^a
TSP with Si	0.06^a	0.09^a	0.09^a	0.16^b	0.10^a	0.07^a	0.10^a	0.14^a	0.13^a	0.11^a
TSP with Mg			0.11^a					0.12^a		

* Means of 3 reps expressed as per cent of dry weight

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability

Table 5. Influence of rate and source of P applied to the Lualualei soil on P concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	0.13^{a}	0.15^{a}	0.17^{a}	0.17^{a}	0.15^{a}	0.09^{a}	0.09^{a}	0.10^{a}	0.13^{a}	0.10^{a}
TSP	0.13^{a}	0.14^{a}	0.14^{a}	0.17^{a}	0.14^{a}	0.09^{a}	0.08^{a}	0.11^{a}	0.11^{a}	0.10^{a}

*Means of 3 reps expressed as per cent of dry weight.

**Means of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

Table 6. Influence of rate and source of P applied to the Halii soil on P uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	0.7^a	13.6^a	26.0^a	38.5^a	19.7^a	0.4^a	13.6^a	40.4^a	55.1^a	27.4^a
TSP	0.7^a	15.1^a	26.3^b	49.0^b	22.8^b	0.4^a	19.7^b	31.6^b	48.3^b	25.0^a
TSP with Si	0.7^a	17.8^a	26.3^b	52.8^b	24.4^b	0.4^a	18.5^b	38.7^a	56.1^a	28.4^a
TSP with Mg			27.9^b					31.3^b		

* Means of 3 reps expressed as mg/pot

** Means of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability

Table 7. Influence of rate and source of P applied to the Lualualei soil on P uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	25.9[a]	42.1[a]	52.3[a]	65.0[a]	46.3[a]	25.2[a]	46.3[a]	55.4[a]	85.2[a]	53.1[a]
TSP	23.6[a]	47.8[b]	56.4[a]	72.4[b]	50.0[a]	21.3[a]	43.6[a]	64.0[b]	70.1[b]	49.7[a]

* Means of 3 reps expressed as mg/pot.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 8. Influence of rate and granule size of FMP applied to the Halii soil on P concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS+	0.06^{a}	0.10^{a}	0.12^{a}	0.12^{a}	0.10^{a}	0.07^{a}	0.12^{ab}	0.13^{a}	0.14^{a}	0.12^{ab}
CF++	0.06^{a}	0.11^{a}	0.10^{a}	0.11^{a}	0.10^{a}	0.07^{a}	0.13^{b}	0.15^{b}	0.16^{b}	0.13^{b}
FF+++	0.06^{a}	0.09^{a}	0.12^{a}	0.13^{a}	0.10^{a}	0.07^{a}	0.10^{a}	0.13^{a}	0.13^{a}	0.11^{a}

* Means of 3 reps expressed as per cent of dry weight.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 9. Influence of rate and granule size of FMP applied to the Halii soil on P uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS[+]	0.7^{a}	13.6^{a}	26.0^{a}	38.5^{a}	19.7^{a}	0.4^{a}	13.6^{a}	40.4^{a}	55.1^{a}	27.4^{a}
CF[++]	0.7^{a}	18.9^{b}	24.4^{a}	35.3^{a}	19.8^{a}	0.2^{a}	26.6^{b}	52.1^{b}	62.7^{b}	35.4^{b}
FF[+++]	0.7^{a}	13.1^{a}	24.7^{a}	42.6^{b}	20.3^{a}	0.3^{a}	17.1^{a}	40.5^{a}	45.0^{c}	25.7^{a}

* Means of 3 reps expressed as mg/pot

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 10. Influence of rate and source of P applied to the Halii soil on Mg concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	0.30^{a}	0.43^{a}	0.57^{a}	0.83^{a}	0.53^{a}	0.30^{a}	0.51^{a}	0.63^{a}	0.87^{a}	0.58^{a}
TSP	0.31^{a}	0.32^{b}	0.44^{b}	0.51^{b}	0.39^{b}	0.31^{a}	0.56^{a}	0.53^{b}	0.47^{b}	0.47^{b}
TSP with Si	0.31^{a}	0.41^{a}	0.45^{b}	0.52^{b}	0.42^{b}	0.31^{a}	0.57^{a}	0.51^{b}	0.45^{b}	0.46^{b}
TSP with Mg			0.57^{a}					0.65^{a}		

* Means of 3 reps expressed as per cent of dry weight

** Means of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability

Table 11. Influence of rate and source of P applied to the Lualualei soil on Mg concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	0.43[a]	0.53[a]	0.57[a]	0.60[a]	0.53[a]	0.59[a]	0.75[a]	0.82[a]	0.92[a]	0.77[a]
TSP	0.41[a]	0.52[a]	0.55[a]	0.62[a]	0.53[a]	0.58[a]	0.75[a]	0.86[a]	0.79[b]	0.75[a]

* Means of 3 reps expressed as per cent of dry weight

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 12. Influence of rate and source of P applied to the Halii soil on Mg uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	3.2^{a}	60.3^{a}	124.5^{a}	265.0^{a}	113.2^{a}	1.6^{a}	65.4^{a}	194.7^{a}	317.6^{a}	144.8^{a}
TSP	3.5^{a}	58.0^{a}	116.7^{a}	154.5^{b}	83.2^{b}	1.6^{a}	109.9^{b}	134.0^{b}	177.6^{b}	105.8^{b}
TSP with Si	3.5^{a}	83.8	130.6^{a}	167.8^{b}	96.4^{b}	1.6^{a}	108.8^{b}	143.4^{b}	187.9^{b}	110.4^{b}
TSP with Mg			144.8^{b}					169.6^{a}		

* Means of 3 reps expressed as mg/pot.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 13. Influence of rate and source of P applied to the Lualualei soil on Mg uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	88.1^{a}	149.7^{a}	179.6^{a}	225.0^{a}	160.6^{a}	160.4^{a}	407.1^{a}	472.7^{a}	628.5^{a}	417.3^{a}
TSP	77.0^{a}	181.2^{b}	219.5^{b}	260.1^{b}	184.5^{b}	161.5^{a}	427.6^{a}	517.8^{b}	506.0^{b}	403.2^{a}

* Means of 3 reps expressed as mg/pot

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 14. Influence of rate and granule size of FMP applied to the Halii soil on Mg concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS+	0.30a	0.43a	0.57a	0.83a	0.53a	0.30a	0.51a	0.63a	0.87a	0.58a
CF++	0.29a	0.50a	0.62a	0.78a	0.55a	0.30a	0.72b	0.81b	0.61b	0.61a
FF+++	0.30a	0.56a	0.57a	0.87a	0.57a	0.31a	0.77b	0.80b	0.59b	0.62a

* Means of 3 reps expressed as per cent of dry weight.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 15. Influence of rate and granule size of FMP applied to the Halii soil on Mg uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean*
FMP										
NS+	3.2^{a}	60.3^{a}	124.5^{a}	265.0^{ab}	113.2^{a}	1.6^{a}	65.4^{a}	194.7^{a}	317.6^{a}	144.8^{a}
CF++	3.0^{a}	85.5^{b}	150.6^{b}	241.6^{a}	120.2^{a}	0.9^{a}	143.5^{b}	289.0^{b}	381.6^{b}	203.8^{b}
FF+++	3.0^{a}	81.0^{b}	117.4^{a}	284.7^{b}	121.5^{a}	1.4^{a}	137.1^{b}	258.2^{b}	334.9^{a}	182.9^{b}

* Means of 3 reps expressed as mg/pot.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 16. Influence of rate and source of P applied to the Halii soil on Si concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	1.16^{a}	0.81^{a}	0.95^{a}	1.21^{a}	1.03^{a}	1.29^{a}	0.71^{ab}	0.89^{a}	1.23^{a}	1.03^{a}
TSP	1.10^{a}	0.52^{b}	0.37^{b}	0.40^{b}	0.60^{b}	1.27^{a}	0.63^{b}	0.56^{b}	0.65^{b}	0.78^{b}
TSP with Si	1.10^{a}	0.58^{b}	0.51^{c}	0.73^{c}	0.73^{c}	1.27^{a}	0.80^{ac}	0.88^{a}	1.03^{c}	1.00^{a}
TSP with Mg			0.45^{d}					0.69^{b}		

* Means of 3 reps expressed as per cent of dry weight.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 17. Influence of rate and source of P applied to the Lualualei soil on Si concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	1.62[a]	1.51[a]	1.55[a]	1.68[a]	1.57[a]	1.68[a]	1.85[a]	2.06[a]	2.18[a]	1.95[a]
TSP	1.65[a]	1.32[a]	1.36[a]	1.50[a]	1.46[a]	1.68[a]	1.77[a]	1.85[a]	1.97[a]	1.82[a]

* Means of 3 reps expressed as per cent of dry weight.

** Mean of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

Table 18. Influence of rate and source of P applied to the Halii soil on Si uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	12.5^{a}	111.3^{a}	207.7^{a}	388.8^{a}	180.1^{a}	6.9^{a}	87.9^{a}	266.3^{a}	449.0^{a}	202.5^{a}
TSP	12.5^{a}	93.8^{a}	98.9^{b}	123.8^{b}	82.2^{b}	6.4^{a}	124.8^{b}	143.0^{b}	241.0^{b}	128.8^{b}
TSP with Si	12.5^{a}	118.6^{a}	150.0^{c}	236.9^{c}	129.5^{c}	6.4^{a}	155.2^{c}	249.7^{a}	432.3^{a}	210.9^{a}
TSP with Mg			114.3^{b}					180.1^{c}		

* Means of 3 reps expressed as mg/pot.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 19. Influence of rate and source of P applied to the Lualualei soil on Si uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	332.2[a]	427.3[a]	490.3[a]	592.5[a]	460.6[a]	457.2[a]	991.6[a]	1113.6[a]	1362.0[a]	981.1[a]
TSP	306.6[a]	463.8[a]	545.2[a]	625.9[a]	485.3[a]	419.2[a]	1001.7[a]	1234.1[a]	1327.0[a]	995.5[a]

* Means of 3 reps expressed as mg/pot.

** Means of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

Table 20. Influence of rate and granule size of FMP applied to the Halii soil on Si concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS+	1.16^{a}	0.81^{a}	0.95^{a}	1.21^{a}	1.03^{a}	1.29^{a}	0.71^{a}	0.89^{a}	1.23^{a}	1.03^{a}
CF++	1.16^{a}	0.89^{a}	0.89^{a}	1.08^{b}	1.01^{a}	1.29^{a}	0.99^{b}	0.83^{a}	1.19^{a}	1.08^{a}
FF+++	1.19^{a}	1.06^{b}	1.13^{b}	1.35^{c}	1.18^{b}	1.30^{a}	1.02^{b}	0.89^{a}	1.41^{b}	1.16^{a}

* Means of 3 reps expressed as per cent of dry weight

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 21. Influence of rate and granule size of FMP applied to the Halii soil on Si uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS+	12.5a	111.3a	207.7a	388.8a	180.1a	6.9a	87.9a	266.3a	449.0a	202.5a
CF++	12.2a	153.3b	218.4a	335.9b	179.9a	4.4a	174.4b	298.8a	478.7a	239.1a
FF+++	11.8a	153.0b	234.4a	440.2c	209.9a	6.8a	181.1b	279.8a	502.9a	242.7a

* Means of 3 reps expressed as mg/pot.

** Means of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 22. Influence of rate and source of P applied to the Halii soil on Ca concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	0.21[a]	0.26[a]	0.34[a]	0.50[a]	0.33[a]	0.25[a]	0.37[a]	0.65[a]	0.54[a]	0.45[a]
TSP	0.21[a]	0.26[a]	0.39[a]	0.58[a]	0.36[a]	0.27[a]	0.51[b]	0.64[a]	0.59[a]	0.50[a]
TSP with Si	0.21[a]	0.41[b]	0.52[b]	0.86[b]	0.50[b]	0.27[a]	0.65[c]	0.77[b]	0.63[a]	0.58[a]
TSP with Mg			0.41[ab]					0.63[a]		

* Means of 3 reps expressed as per cent of dry weight.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 23. Influence of rate and source of P applied to the Lualualei soil on Ca concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	0.30[a]	0.36[a]	0.39[a]	0.43[a]	0.37[a]	0.41[a]	0.51[a]	0.51[a]	0.54[a]	0.49[a]
TSP	0.31[a]	0.38[a]	0.39[a]	0.45a	0.38[a]	0.43[a]	0.50[a]	0.54[a]	0.60[a]	0.52[a]

* Means of 3 reps expressed as per cent of dry weight

** Means of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

Table 24. Influence of rate and source of P applied to the Halii soil on Ca uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	2.3^{a}	35.2^{a}	75.0^{a}	159.1^{a}	67.9^{a}	1.3^{a}	48.2^{a}	184.4^{a}	207.8^{a}	110.4^{a}
TSP	2.3^{a}	46.5^{a}	104.7^{b}	178.1^{b}	82.9^{b}	1.4^{a}	101.1^{b}	164.3^{a}	296.9^{b}	140.9^{b}
TSP with Si	2.3^{a}	85.1^{b}	151.0^{c}	276.5^{c}	128.7^{c}	1.4^{a}	123.1^{c}	248.3^{b}	412.9^{c}	196.4^{c}
TSP with Mg			104.1^{b}					164.4^{a}		

* Means of 3 reps expressed as mg/pot.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 25. Influence of rate and source of P applied to the Lualualei soil on Ca uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	62.0^{a}	101.6^{a}	123.4^{a}	161.2^{a}	112.1^{a}	110.7^{a}	275.7^{a}	293.8^{a}	367.9^{a}	262.0^{a}
TSP	56.9^{a}	135.4^{b}	156.4^{b}	186.2^{b}	133.7^{b}	114.5^{a}	283.4^{a}	324.7^{b}	382.6^{a}	276.3^{a}

* Means of 3 reps expressed as mg/pot.

** Means of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 26. Influence of rate and granule size of FMP applied to the Halii soil on Ca concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS+	0.21^{a}	0.26^{a}	0.34^{a}	0.50^{a}	0.33^{a}	0.25^{a}	0.37^{a}	0.54^{a}	0.64^{a}	0.45^{a}
CF++	0.17^{a}	0.28^{a}	0.34^{a}	0.45^{a}	0.31^{a}	0.26^{a}	0.51^{b}	0.56^{a}	0.56^{a}	0.47^{a}
FF+++	0.19^{a}	0.30^{a}	0.34^{a}	0.53^{a}	0.34^{a}	0.26^{a}	0.49^{b}	0.57^{a}	0.58^{a}	0.48^{a}

* Means of 3 reps expressed as per cent of dry weight.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 27. Influence of rate and granule size of FMP applied to the Halii soil on Ca uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS^{+}	2.3^{a}	35.2^{a}	75.0^{a}	159.1^{ab}	67.9^{a}	1.3^{a}	48.2^{a}	184.4^{a}	207.8^{a}	110.4^{a}
CF^{++}	1.8^{a}	48.7^{a}	83.6^{a}	139.5^{b}	68.4^{a}	0.8^{a}	107.9^{b}	182.6^{a}	223.2^{a}	128.6^{a}
FF^{+++}	1.9^{a}	43.7^{a}	71.2^{a}	168.2^{ac}	71.3^{a}	1.2^{a}	102.3^{b}	159.1^{a}	203.1^{a}	116.4^{a}

* Means of 3 reps expressed as mg/pot.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 28. Influence of rate and source of P applied to the Halii soil on K concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	1.58[a]	2.54[a]	1.68[a]	1.02[a]	1.71[a]	1.34[a]	2.54[a]	1.83[a]	1.05[a]	1.69[a]
TSP	1.67[a]	1.97[b]	1.32[b]	1.12[a]	1.52[b]	1.25[a]	1.72[b]	1.40[b]	0.95[ab]	1.33[b]
TSP with Si	1.67[a]	1.63[c]	1.14[c]	1.15[a]	1.40[b]	1.25[a]	1.83[b]	1.65[c]	0.79[b]	1.38[b]
TSP with Mg			1.34[b]					1.27[b]		

* Means of 3 reps expressed as per cent of dry weight.

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 29. Influence of rate and source of P applied to the Lualualei soil on K concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	3.46^{a}	2.96^{a}	2.86^{a}	2.54^{a}	2.96^{a}	1.70^{a}	0.92^{a}	0.78^{a}	0.88^{a}	1.07^{a}
TSP	3.49^{a}	2.63^{a}	2.38^{b}	2.30^{a}	2.70^{a}	1.72^{a}	0.79^{a}	0.83a	0.84^{a}	1.04^{a}

* Means of 3 reps expressed as per cent of dry weight.

** Means of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 30. Influence of rate and source of P applied to the Halii soil on K uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP(NS)	17.2^{a}	333.6^{a}	362.3^{a}	326.7^{a}	260.0^{a}	7.2^{a}	312.4^{a}	565.5^{a}	383.3^{a}	317.1^{a}
TSP	19.1^{a}	356.5^{a}	339.0^{a}	344.0^{a}	250.5^{a}	6.3^{a}	338.9^{a}	352.3^{b}	355.3^{a}	263.2^{a}
TSP with Si	19.1^{a}	334.0^{a}	333.4^{a}	372.7^{a}	245.1^{a}	6.3^{a}	352.4^{a}	463.9^{c}	330.5^{a}	288.3^{a}
TSP with Mg			340.4^{a}					331.1^{b}		

* Means of 3 reps expressed as mg/pot

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 31. Influence of rate and source of P applied to the Lualualei soil on K uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	50	100	200	Mean**	0	50	100	200	Mean**
FMP	709.9[a]	823.7[a]	896.7[a]	953.8[a]	846.0[a]	454.1[a]	488.7[a]	446.0[a]	597.1[a]	496.5[a]
TSP	649.1[a]	918.3[b]	956.7[a]	956.1[a]	870.1[a]	446.0[a]	446.6[a]	495.3[a]	526.6[a]	478.6[a]

* Means of 3 reps expressed as mg/pot.

** Means of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

Table 32. Influence of rate and granule size of FMP applied to the Halii soil on K concentration in Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS+	1.58a	2.54a	1.68a	1.02a	1.71a	1.34a	2.54a	1.83a	1.05a	1.69a
CF++	1.52a	1.94a	1.43a	0.99a	1.47a	1.29a	1.72a	1.22a	0.78a	1.25a
FF+++	1.47a	2.25a	1.73a	0.89a	1.58a	1.26a	1.77a	1.37a	0.90a	1.33a

* Means of 3 reps expressed as per cent of dry weight.

** Mean of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 33. Influence of rate and granule size of FMP applied to the Halii soil on K uptake by Sudax*

Phosphate Treatment	Plant Crop					Ratoon Crop				
	kgP/ha									
	0	100	300	800	Mean**	0	100	300	800	Mean**
FMP										
NS+	17.2a	333.6a	362.3a	326.7a	260.0a	7.2a	312.4a	565.5a	383.3a	317.1a
CF++	15.9a	332.4a	345.6a	307.9a	250.5a	4.5a	339.5a	425.7b	311.8b	270.4b
FF+++	14.2a	326.6a	349.3a	290.3a	245.1a	6.0a	313.6a	436.1b	321.3b	269.2b

* Means of 3 reps expressed as mg/pot.

** Means of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 34. Influence of rate and source of applied P on 0.5M $NaHCO_3$-extractable soil P*

Phosphate Treatment	Halii Soil					Lualualei Soil				
	kgP/ha									
	0	100	300	800	Mean**	0	50	100	200	Mean**
FMP(NS)	4.3^{a}	5.7^{a}	11.3^{a}	26.7^{a}	12.0^{a}	11.7^{a}	16.3^{a}	35.7^{a}	57.0^{a}	30.2^{a}
TSP	5.0^{a}	12.0^{b}	18.0^{b}	30.7^{b}	16.4^{b}	10.7^{a}	17.3^{a}	49.0^{b}	63.0^{b}	35.0^{b}
TSP with Si	5.0^{a}	16.3^{c}	27.3^{c}	37.7^{c}	21.6^{c}					
TSP with Mg			18.0							

* Means of 3 reps expressed as ppm

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 35. Influence of rate and source of applied P on modified Truog - extractable soil P*

Phosphate Treatment	Halii Soil					Lualualei Soil				
	kgP/ha									
	0	100	300	800	Mean**	0	50	100	200	Mean**
FMP(NS)	23.3 [a]	51.7 [a]	58.3 [a]	125.0 [a]	64.6 [a]	51.7 [a]	63.7 [a]	71.7 [a]	116.7 [a]	75.9 [a]
TSP	20.7 [a]	64.3 [b]	73.3 [b]	151.3 [b]	77.4 [b]	48.0 [a]	68.3 [a]	88.0 [a]	123.3 [a]	81.9 [a]
TSP with Si	20.7 [a]	80.0 [c]	101.7 [c]	160.7 [c]	90.8 [c]					
TSP with Mg			76.0							

* Means of 3 reps expressed as ppm

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 36. Influence of rate and granule size of FMP applied to Halii soil on 0.5M $NaHCO_3$-extractable soil P*

Phosphate Treatment	kgP/ha 0	100	300	800	Mean**
FMP					
NS+	4.3[a]	5.7[a]	11.3[a]	26.7[a]	12.0[a]
CF++	5.3[a]	8.0[b]	12.3[a]	32.0[b]	14.4[b]
FF+++	4.7[a]	9.3[b]	7.7[b]	18.0[c]	9.9[c]

* Means of 3 reps expressed as ppm

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 37. Influence of rate and granule size of FMP applied to Halii soil in modified Truog-extractable soil P*

Phosphate Treatment	kgP/ha 0	100	300	800	Mean**
FMP					
NS+	23.3^{a}	51.7^{a}	58.3^{a}	125.0^{a}	64.6^{a}
CF++	23.3^{a}	56.3^{b}	68.0^{b}	142.0^{b}	72.4^{b}
FF+++	22.3^{a}	40.7^{c}	51.7^{c}	120.0^{c}	58.7^{c}

*Means of 3 reps expressed as ppm

**Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 38. Influence of rate and source of applied P on P sorption Studies*

Halii Soil

P kg/ha	FMP (NS) ugP/g soil 0	100	250	500	1000	FMP (CF) ugP/g soil 0	100	250	500	1000	FMP (FF) ugP/g soil 0	100	250	500	1000
0	".0000"	.0017	.0050	.0140	.0500										
100	.0019	.0040	.0100	.0250	.0940	.0020	.0045	.0105	.0280	.0100	.0015	.0033	.0077	.0210	.0940
300	.0025	.0050	.0110	.0320	.0140	.0035	.0062	.0130	.0360	.1800	.0030	.0058	.0120	.0320	.1300
800	.0045	.0080	.0170	.0540	.3150	.0062	.0110	.0200	.0540	.3150	.0030	.0059	.0135	.0415	.2800

Halii Soil

P kg/ha	TSP ugP/g soil 0	100	250	500	1000	TSP+Si ugP/g soil 0	100	250	500	1000
0										
100	.0028	.0058	.0110	.0225	.0600	.0040	.0068	.0135	.0350	.1300
300	.0030	.0062	.0120	.0340	.1600	.0036	.0076	.0150	.0400	.1750
800	.0050	.0100	.0230	.0680	.2700	.0070	.0140	.0300	.0900	.4250

Lualualei Soil

P kg/ha	FMP ugP/g soil 0	25	50	100	TSP ugP/g soil 0	25	50	100
0	.20	.40	.80	1.50				
50	.23	.44	.73	1.80	.29	.50	.78	1.60
100	.21	.42	.74	1.70	.25	.42	.70	1.60
200	.22	.48	.80	1.85	.22	.56	.96	1.90

* Values are ppm P in solution

Table 39. Influence of rate and source of applied P on neutral 1N NH_4OAc-extractable soil Mg*

Phosphate Treatment	Halii Soil					Lualualei Soil				
	kgP/ha									
	0	100	300	800	Mean**	0	50	100	200	Mean**
FMP(NS)	3.7^{a}	4.7^{a}	6.7^{a}	8.7^{a}	5.9^{a}	33.0^{a}	34.9^{a}	32.0^{a}	30.9^{a}	32.7^{a}
TSP	3.7^{a}	2.5^{a}	2.6^{b}	1.9^{b}	2.7^{b}	32.5^{a}	29.9^{b}	29.2^{b}	25.7^{b}	29.3^{b}
TSP with Si	3.7^{a}	2.7^{a}	2.1^{b}	1.0^{b}	2.4^{b}					
TSP with Mg			3.2^{b}							

* Means of 3 reps expressed as me/100 g soil

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 40. Influence of rate and granule size of FMP applied to Halii soil on neutral 1N NH_4OAc-extractable soil Mg*

Phosphate Treatment	kgP/ha				
	0	100	300	800	Mean**
FMP					
NS+	3.7a	4.7a	6.7a	8.7a	5.9a
CF++	4.9a	5.1a	6.6a	8.2a	6.2a
FF+++	4.0a	4.9a	5.8b	6.3b	5.3b

* Means of 3 reps expressed as me/100 g soil

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 41. Influence of rate and source of applied P on water-extractable soil Si*

Phosphate Treatment	Halii Soil					Lualualei Soil				
	kgP/ha									
	0	100	300	800	Mean**	0	50	100	200	Mean**
FMP(NS)	4.7[a]	4.2[a]	3.7[a]	8.2[a]	5.2[a]	7.9[a]	6.6[a]	6.7[a]	7.0[a]	7.1[a]
TSP	3.5[a]	2.8[b]	2.7[a]	3.0[b]	3.0[b]	8.8[a]	6.0[a]	6.7[a]	7.0[a]	7.1[a]
TSP with Si	3.5[a]	3.3[b]	3.8[a]	5.0[c]	3.9[b]					
TSP with Mg			2.8[a]							

* Means of 3 reps expressed as ppm

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 42. Influence of rate and granule size of FMP applied to Halii soil on water-extractable soil Si*

Phosphate Treatment	kgP/ha 0	100	300	800	Mean**
FMP					
NS+	4.7a	4.7a	3.7a	8.2a	5.2a
CF++	3.8a	3.4b	4.6b	8.5a	5.1a
FF+++	3.9a	3.1b	4.8b	4.6b	4.1b

* Means of 3 reps expressed as ppm

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 43. Influence of rate and source of applied P on neutral 1N NH_4OAc - extractable soil Ca*

Phosphate Treatment	Halii Soil					Lualualei Soil				
	kgP/ha									
	0	100	300	800	Mean**	0	50	100	200	Mean**
FMP(NS)	2.4[a]	2.5[a]	4.0[a]	5.4	3.6[a]	22.4[a]	22.7[a]	23.3[a]	23.9[a]	23.1[a]
TSP	2.1[a]	2.1[a]	2.2[b]	3.7	2.5[b]	22.5[a]	22.6[a]	22.9[a]	23.8[a]	22.9[a]
TSP with Si	2.1[a]	3.9[b]	4.5[ac]	6.2	4.2[ac]					
TSP with Mg			3.3							

* Means of 3 reps expressed as me/100 g soil

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

Table 44. Influence of rate and granule size of FMP applied to Halii soil on neutral 1N NH_4OAc - extractable soil Ca*

Phosphate Treatment	kgP/ha				
	0	100	300	800	Mean**
FMP					
NS+	2.4[a]	3.9[a]	4.0[a]	5.4[a]	3.9[a]
CF++	2.2[a]	2.8[b]	3.6[a]	5.0[a]	3.4[a]
FF+++	2.2[a]	2.5[b]	3.1[a]	5.6[a]	3.4[a]

* Means of 3 reps expressed as me/100 g soil

** Mean of 12 observations. Means followed by different letters are significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 45. Influence of rate and form of applied P on neutral 1N NH_4OAc - extractable Soil K*

Phosphate Treatment	Halii Soil					Lualualei Soil				
	kgP/ha									
	0	100	300	800	Mean**	0	50	100	200	Mean**
FMP (NS)	0.7[a]	0.3[a]	0.3[a]	0.2[a]	0.4[a]	0.6[a]	0.4[a]	0.4[a]	0.3[a]	0.4[a]
TSP	0.7[a]	0.2[a]	0.2[a]	0.2[a]	0.3[a]	0.7[a]	0.4[a]	0.4[a]	0.3[a]	0.5[a]
TSP with Si	0.7[a]	0.2[a]	0.2[a]	0.2[a]	0.3[a]					
TSP with Mg			0.2[a]							

* Means of 3 reps expressed as me/100 g soil

** Mean of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

Table 46. Influence of rate and granule size of FMP applied to Halii soil on neutral 1N NH_4OAc - extractable soil K*

Phosphate Treatment	kgP/ha				
	0	100	300	800	Mean**
FMP					
NS+	0.7^a	0.3^a	0.3^a	0.2^a	0.4^a
CF++	0.6^a	0.2^a	0.2^a	0.2^a	0.3^a
FF+++	0.9^a	0.2^a	0.2^a	0.2^a	0.4^a

* Means of 3 reps expressed as me/100 g soil

** Mean of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 47. Influence of rate and form of applied P on soil pH*

Phosphate Treatment	Halii Soil					Lualualei Soil				
	kgP/ha									
	0	100	300	800	Mean**	0	50	100	200	Mean**
FMP(NS)	4.1^a	4.5^a	5.1^a	5.6^a	4.8^a	7.2^a	7.5^a	7.7^a	7.7^a	7.5^a
TSP	4.1^a	4.6^a	4.9^a	5.0^a	4.7^a	7.2^a	7.5^a	7.5^a	7.4^a	7.4^a
TSP with Si	4.1^a	4.9^a	5.1^a	5.3^a	4.8^a					
TSP with Mg			5.0^a							

* 1:1 soil-water suspension values are means of 3 reps.

** Mean of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

Table 48. Influence of rate and granule size of FMP applied to the Halii soil on 1N KCl-extractable soil Al and soil pH

Phosphate Treatment	Soil Al*					Soil pH**				
	kgP/ha									
	0	100	300	800	Mean***	0	100	300	800	Mean***
FMP										
NS+	0.7^{a}	0.5^{a}	0.3^{a}	0.2^{a}	0.4^{a}	4.1^{a}	4.5^{a}	5.1^{a}	5.6^{a}	4.8^{a}
CF++	0.6^{a}	0.4^{a}	0.3^{a}	0.2^{a}	0.4^{a}	4.4^{a}	4.8^{a}	5.1^{a}	5.5^{a}	5.0^{a}
FF+++	0.7^{a}	0.4^{a}	0.3^{a}	0.1^{a}	0.4^{a}	4.1^{a}	5.0^{a}	5.1^{a}	5.8^{a}	5.0^{a}

* Means of 3 reps expressed as me/100 g soil

** 1:1 soil-water suspension. Values are means of 3 reps.

*** Mean of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

\+ Normal size fraction

++ Coarse fraction

+++ Fine fraction

Table 49. Influence of rate and source of P applied to the Halii soil on 1N KCl-extractable soil Al*

Phosphate Treatment	kgP/ha 0	100	300	800	Mean**
FMP(NS)	0.7[a]	0.5[a]	0.3[a]	0.2[a]	0.4[a]
TSP	0.7[a]	0.5[a]	0.4[a]	0.4[a]	0.5[a]
TSP with Si	0.7[a]	0.4[a]	0.3[a]	0.3[a]	0.4[a]
TSP with Mg			0.4[a]		

* Means of 3 reps expressed as me/100 g soil

** Mean of 12 observations. Means followed by the same letter are not significantly different (BLSD test) at the 5% level of probability.

Appendix C

List of Scientific Names of Plant Crops

Banana	*Musa spp*
Barley	*Hordeum vulgare*
Berseem	*Medicago sativa*
Corn	*Zea Mays*
Desmodium	*Desmodium intortum*
Kikuyu grass	*Pennesitum clandestinum*
Millet	*Pennisetum typhoides*
Papaya	*Carica papaya*
Rice	*Oryzae sativa*
Sorghum	*Sorghum bicolor*
Sudan grass	*S. sudanense*
Sudax	*S. bicolor* x *S. sudanense*
Sugar cane	*Saccharum officinarum*
Sweet potato	*Ipomoea batata*
Taro	*Colocasia esculenta*
Tomato	*Lycopersicon esculentum*
Wheat	*Triticum aestivum*

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